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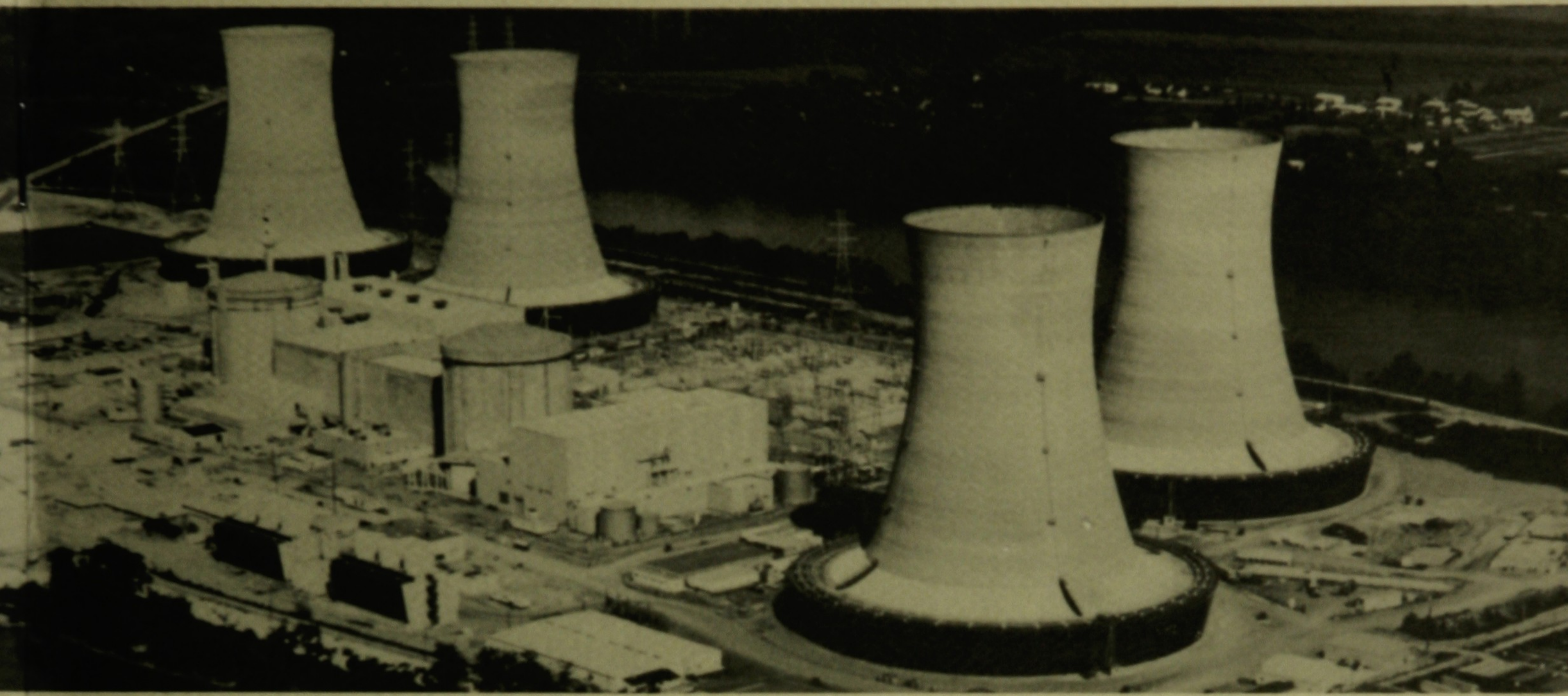

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POST-ACCIDENT EXAMINATION OF PLATINUM RESISTANCE THERMOMETERS INSTALLED IN THE TMI-2 REACTOR

R. M. Carroll
R. L. Shepard

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R. M. Carroll
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Oak Ridge National Laboratory
Oak Ridge, Tennessee

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ABSTRACT

Laboratory tests conducted on one resistance thermometer and thermowell removed from TMI-2 showed that neither its calibration nor its time response was adversely affected by the accident or post-accident conditions to which it had been exposed. No Never-Seez was used in its thermowell. A broken conduit fitting allowed moisture to enter the extension cables, which affected their insulation resistance. Tests on similar thermometers installed in TMI-2 and Crystal River Unit 3 at shutdown and at full power showed that the time response of the TMI-2 thermometer met the 5-second limit required by the plant technical specifications.

SUMMARY

A "worst-case" platinum resistance thermometer (PRT) removed from Unit 2 of the Three Mile Island Reactor (TMI-2) four years after the March 1979 accident was found to conform to the original purchase specifications for calibration, response time, and electrical properties. In addition to verifying the benchmark response time (in 170°F water flowing at 3 fps), we confirmed that the response time of this PRT at full-power conditions (550°F and 50 fps) met plant technical specifications.

The particular PRT selected for removal on the basis of in-situ tests had the lowest insulation resistance and heat transfer coefficient of all seven PRTs tested in situ in the hot and cold legs of loops A and B of TMI-2. Since this PRT met specifications in post-removal tests, we infer that the remainder of the PRTs would also meet specifications.

Although the PRTs apparently were not harmed by the accident, partial shorting of the extension cables during the accident may have caused erroneous temperature readings. The protective conduit connection to the thermometer head was found to be broken on the worst-case PRT, allowing steam to enter the connecting terminal housing and the cable during the accident. All but two of the PRTs tested showed evidence of moisture in the measuring circuit.

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POST-ACCIDENT EXAMINATION OF PLATINUM RESISTANCE THERMOMETERS INSTALLED IN THE TMI-2 REACTOR

1. PROBLEM STATEMENT

In order to assess the validity of the temperatures of the TMI-2 reactor coolant measured during and after the reactor accident, the three problems listed in the following paragraphs had to be solved.

1.1 Possible Decalibration of PRTs

The temperatures of the primary coolant water in the TMI-2 reactor were measured by PRTs installed in thermowells. During the accident the PRTs were subjected to excessive temperatures, vibration, and radiation. After the reactor was shut down, the PRTs continued to be subjected to gamma radiation from the fission products deposited in the coolant loops. We undertook to determine whether the PRTs were still in calibration or, if not, assess the amount and cause of the decalibration.

1.2 Possible Response Time Degradation

Analysis of the coincidence of events during the accident requires a knowledge of the response times of the temperature sensors. The response times could have changed as a result of excessive temperature and/or vibration during the accident. Therefore, we undertook to find whether or not the response time had changed and, if so, to evaluate the cause of the changes.

1.3 Possible Voltage Shunting

The validity of recorded temperatures depends on the assumption that the resistance measured is entirely that of the PRT sensing element. If there were, for example, an unaccounted-for 0.1-MΩ leakage resistance in parallel with the PRT element, a 3°F error would result at the normal reactor operating temperature of 550°F. The output signal from the temperature transmitter may have been degraded by partial shorting between the PRT wires or the extension cable wires.

2. BACKGROUND

In March 1979, the TMI-2 nuclear reactor suffered a loss-of-coolant accident (LOCA). Measurements made by reactor personnel during the accident showed some in-core thermocouples indicating temperatures at or above the melting point of the thermocouple materials (2550°F).[1] The lowered water level in the reactor caused PRTs installed in the hot legs of the coolant loops to be exposed to superheated steam. The PRTs in Loop B exceeded the upper recorder temperature indication limit of 800°F,[2] which is significantly greater than the upper temperature limit of 670°F specified for the PRTs.[3]

During the accident the PRT connecting heads and signal cables are thought to have been subjected to escaping steam, and the PRT seals reached a temperature that was surely higher than normal. In addition, as the accident progressed the primary coolant became a saturated two-phase mixture of increasing void fraction that caused increasing vibration in the circulation pumps, with the result that the Loop B pumps were tripped 73 min into the accident and Loop A pumps were turned off 100 min into the accident in response to indications of low system pressure, high vibration, and low coolant flow. We cannot evaluate the extent of vibration transmitted to the loop by the coolant pumps or caused by water hammers associated with two-phase flow, but it must have been much greater than usual.[2]

It was feared that the combination of excessive temperature, moisture, and vibration had damaged the PRTs. After the accident, Oak Ridge National Laboratory (ORNL) personnel were informed that the PRTs in the core exit lines had failed and that the calibrations of the PRTs in the inlet lines were in doubt.[1]

2.1 PRT Design Considerations and Specifications

The primary coolant temperatures in TMI-2 were measured with Rosemount Engineering Company (REC) Model 177 HW PRTs.[3] The Model 177 HWs are dual-element, 4-wire PRTs with a threaded silver bushing on the sheath surrounding the sensor (Figure 1). The 177 HW PRTs are supplied with a REC calibration chart generated from calibrations at 0°C (32°F), 100°C (212°F), and 316°C (600°F). The calibrations above 0°C are made in oil baths, and an uncertainty of ±0.065°F at 600°F is asserted. Repeatability specifications require that agreement at 600°F be obtained with no more than ±0.30°F deviation from the REC factory calibration. Otherwise it is assumed that the PRT has a strained element or that errors are present in the calibration system.

2.2 Design Considerations to Improve Response Time

When the TMI-2 PRTs were purchased, REC Dwg. No. 177 HW, Rev. M1 (11-11-70) specified a response time of less than 8 s. Before the PRTs were installed, a new specification, REC Dwg. No. H33551-1201, Rev. 1 (5-2-75) required a response time of less than 6.8 s. In both cases the 63.2% response time was measured by plunging the PRT (installed in its thermowell) into 170 ± 10°F water flowing at 3 fps. The response times of the PRTs were measured twice by the manufacturer before installation: first, to certify that they met the 8-s specification and second, that they met the 6.8-s specification.

The threaded silver bushing on the PRT sheath (Figure 1) is intended to improve heat transfer between the PRT sheath and the matched thermowell (Figure 2), thus decreasing the installed response time. The bushing diameter and the mating thermowell are sized so that the bushing threads scrub against the inner surface of the thermowell when the PRT is inserted into the thermowell. It is important to note that the soft silver threads are distorted once the PRT is inserted; therefore, if the PRT is removed and reinserted (or even rotated in the thermowell), the metal-to-metal contact will not be as good as on initial insertion.

REC has recommended that if PRTs are installed in existing (not especially mated) thermowells, or if they are withdrawn and reinserted into a matched thermowell, the silver bushing should be coated with Never-Seez compound.[4] Never-Seez is a suspension of nickel platelets in an organic carrier with a room-temperature consistency of thick grease.

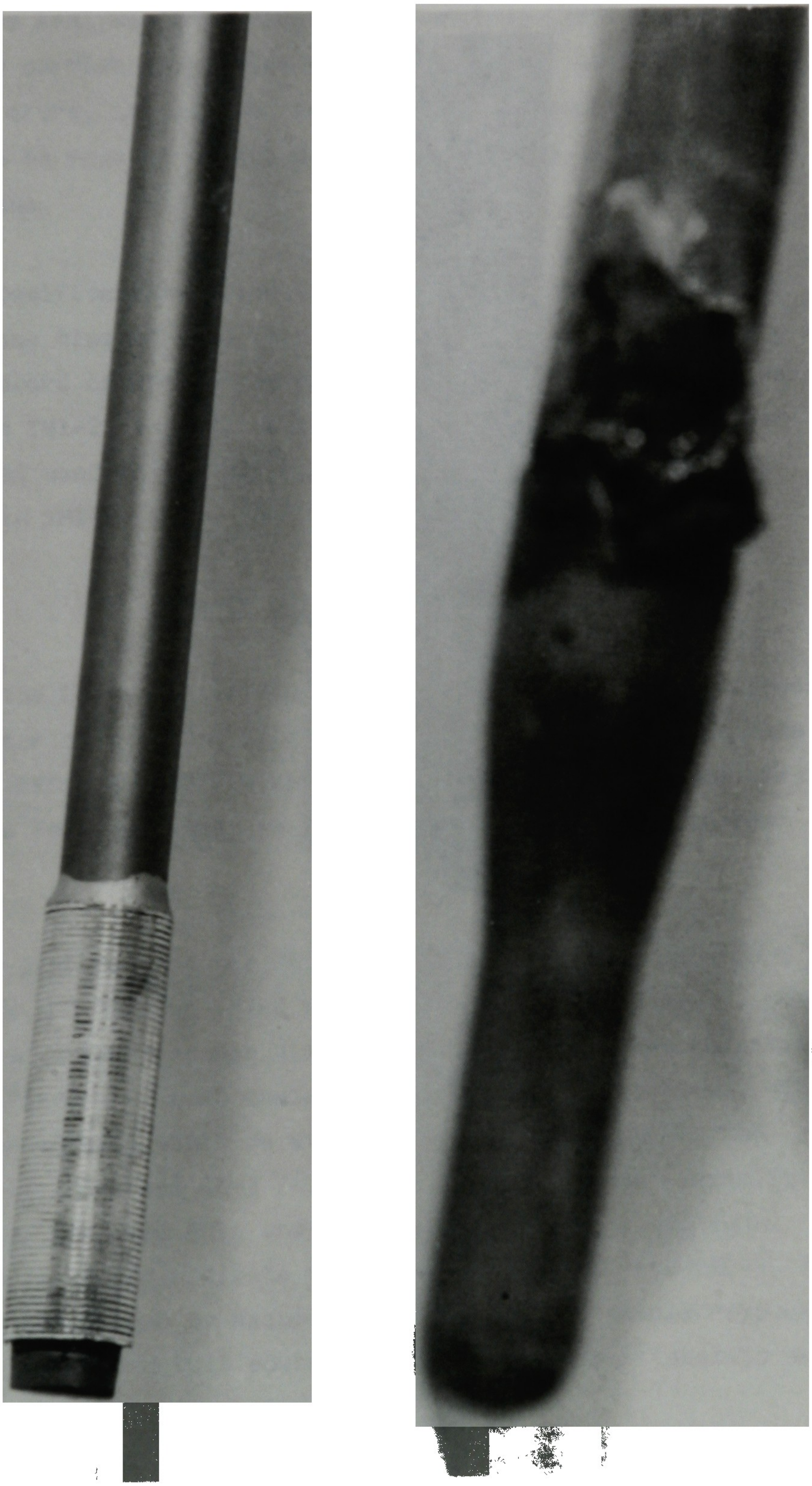

Figure 1. REC Model 177 HW PRT S/N 3670 shows a clean silver bushing.

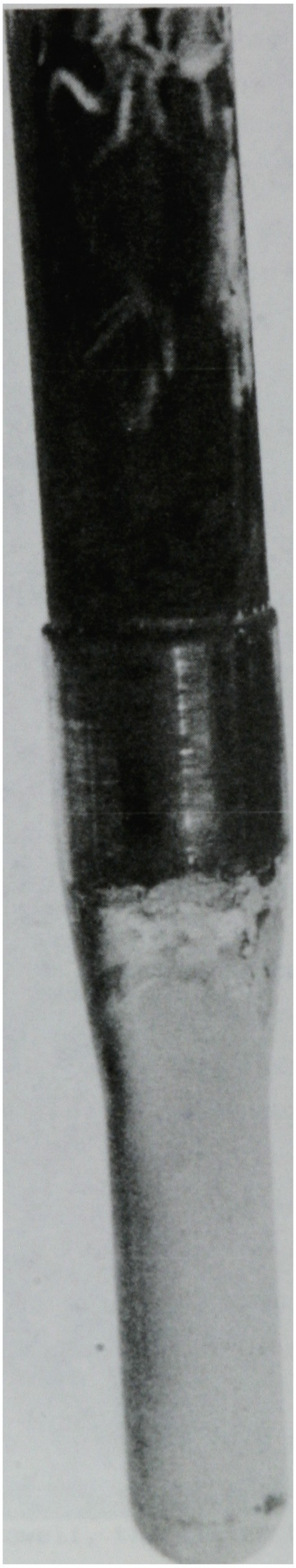

Figure 2. Thermowell for REC Model 177 HW PRT S/N 3670 removed from TMI-2 shows radioactive surface deposits.

However, tests by Analysis and Measurement Services (AMS) have shown that the organic carrier evaporates slowly at reactor operating temperatures[5] and, therefore, the shorter response times obtained by the use of Never-Seez would be negated as the carrier evaporates and leaves only a dry powder residue.

Purchase specifications allow the use of Never-Seez to meet the specified response time of less than 6.8 s in 3 fps water. However, we could find no record of whether Never-Seez was used when the PRTs were installed in the TMI-2 reactor. Later examination showed that Never-Seez had not been used in the PRT removed from TMI-2 nor, presumably, in the other PRTs in TMI-2.

2.3 PRTs in Similar Facilities

Unit 3 of the Crystal River Nuclear Power Plant (CR-3) is a pressurized water reactor of the same type as TMI-2 and was made by the same manufacturer.[6] REC Model 177 HW PRTs were also installed in the CR-3 plant, and these PRTs are known to contain Never-Seez in the thermowells.

Tests were performed on the PRTs in both the TMI-2 and the CR-3 reactors because the PRTs at TMI-2 could be tested only in still, room temperature water. The response time and self-heating characteristics are, however, affected by both coolant flow rate and temperature. These flow-temperature effects could be evaluated by first comparing the response times of TMI-2 and CR-3 PRTs in still water, then measuring the response times of the CR-3 PRTs under reactor operating conditions. From these data, we could estimate the response times of the TMI-2 PRTs under operating conditions by assuming that they would change response time between shutdown and full power with the same proportionality as the CR-3 PRTs.

3. TEST PLAN

The information obtained from the in-situ testing of the PRTs in the TMI-2 reactor included the following:

1. The electrical resistance of the elements and extension wires,
2. The insulation resistance between the extension wires and element circuit, and plant ground,
3. The PRT response time, using the loop-current step-response (LCSR) method,[7] and
4. The self-heating index (SHI) of the PRTs.[8,9]

3.1 In-Situ Testing in TMI-2

Two PRTs each in the hot leg (inlet) of Loops A and B (four PRTs in all) were selected for testing. Two PRTs in the cold leg of Loop A and one PRT in the cold leg of Loop B were selected for testing, but only one element of one PRT in the Loop A cold leg was tested. Thus 13 separate PRT elements in 7 PRTs were given tests (a) through (d) above. Tests were conducted with the water in the coolant loops at ambient temperature and with the circulating pumps off.

3.2 In-Situ Testing in CR-3 at Shutdown and at Full Power

Two PRTs each from the hot and cold legs of Loops A and B of CR-3 were selected for testing. Both elements of each PRT were tested, a total of 16 separate PRT elements in 8 PRTs. In-situ tests were conducted during shutdown with pumps off and ambient-temperature water filling the coolant loops. Later tests were performed under full-power conditions (550°F water flowing at 50 fps). Detailed results are presented in Appendix I.

3.3 PRT-Thermowell Assembly Removed From TMI-2

The PRT removed from TMI-2 for calibration and response testing was taken from the hot leg of Loop A, where during the accident it had reached an indicated temperature of 780°F.[2] This PRT bore the TMI-2 tag

#RC-4A-TE3,4 and the Rosemount S/N 3670. The PRT-thermowell assembly was removed without moving the PRT in relation to the thermowell. This particular PRT was selected for removal because the in-situ insulation resistance measurements indicated that it had suffered the greatest degradation of the PRTs tested. Also, the PRT had the largest SHI of the PRTs tested, implying the poorest heat transfer. Since only one PRT-thermowell assembly was scheduled for removal from TMI-2, it was considered best to select for maximum rather than median damage. Detailed results are presented in Appendix II.

3.4 Sequence of Testing of Assembly Removed From TMI-2

In addition to the four tests listed at the beginning of Section 3, PRT S/N 3670 was to be (a) calibrated, (b) tested for insulation resistance with connecting cables removed, (c) tested for response time as a function of coolant flow and temperature, (d) tested for self-heating as a function of coolant flow and temperature, and (e) removed from the thermowell and examined for evidence of overheating or Never-Seez degradation.

3.5 Chronological Sequence of Tests

3.5.1 In-Situ Tests at TMI-2 (February 1983)

Seven PRTs were tested in-situ (in uncirculated reactor coolant water at ambient temperature) for time response, self-heating, insulation resistance, and loop resistance.

3.5.2 In-Situ Tests at CR-3, Reactor Shut Down (June 1983)

Three PRTs were tested in-situ (in uncirculated reactor coolant water and in slowly moving water at ambient temperature) for time response, self-heating index, insulation resistance, and loop resistance.

3.5.3 In-Situ Tests at CR-3, Reactor at Full Power (March 1984)

Eight PRTs were tested in situ for time response and self-heating index at full power in 557°F water flowing at 52 fps (cold leg) and in 599°F water flowing at 67 fps (hot leg).

3.5.4 PRT-Thermowell Assembly Removed from TMI-2

Assembly from TMI-2 shipped to Idaho National Engineering Laboratory (INEL) April 1, 1984.

3.5.5 Decontamination and Calibration at INEL (April - July 1984)

One PRT (S/N 3670) and thermowell from TMI-2 were tested at INEL for insulation resistance and calibration. The intact assembly was x-rayed. Results and procedures are reported in Appendix III. INEL shipped the PRT-thermowell assembly to ORNL in August 1984.

3.5.6 ORNL Tests on PRT and Thermowell Assembly (September - October 1984)

One PRT (S/N 3670) and thermowell assembly removed from TMI-2 was measured for room-temperature insulation resistance, then tested for response time (by plunge and LCSR) and self-heating index at various water flows and at temperatures to 550°F in a gallium-indium-tin (GIT) eutectic alloy.

3.5.7 PRT and Thermowell Disassembled (November 13, 1984)

PRT S/N 3670 was removed from its thermowell and inspected visually.

3.6 Test Participants and Personnel

AMS participated in tests 3.5.1, 3.5.2, 3.5.3, and 3.5.6; INEL participated in tests 3.5.4 and 3.5.5; and ORNL participated in tests

3.5.1, 3.5.6, and 3.5.7. Persons performing the tests included: H. M. Hashemian, K. E. Holbert, Bruce Jakway, T. M. Kerlin, and K. M. Peterson of AMS; N. H. Ellis, R. L. Rowe, and R. C. Strahm of INEL; and R. M. Carroll and R. L. Shepard of ORNL.

4. TEST METHODS

4.1 Loop Resistance Measurements

The loop resistance of the installed PRT element was measured from the TMI-2 control room and included about 300 ft of extension cable. A calibrated Keithley Model 191 Digital Multimeter (DOE-X-137678) was used for the measurements, referencing a standard 100-Ω resistor between each measurement. Measurements were made in the forward and reverse polarities (see Reference 6 and Appendix I).

4.2 Insulation Resistance

Insulation resistance from the elements to ground was measured at TMI-2 and CR-3 with a calibrated General Radio Megohm Bridge (IC 28287). using an applied voltage of 100 V dc.[6] At INEL, the measurements were made with a Hewlett-Packard Model 4329A insulation resistance meter using an applied voltage of 100 V dc (Appendix II). At ORNL, an uncalibrated Hewlett-Packard Model 4329A set at 100 V dc was verified with a 10^9-Ω standard before being used. All measurements were made in the forward and reverse polarities.

4.3 Self-Heating Index

The self-heating index (SHI) was obtained from the change in element resistance with the change in steady-state electric-power dissipation in the PRT element. Measurements performed by AMS at TMI-2 and CR-3 are described in Appendix I. AMS measured the SHI with a special response time test instrument having calibration traceable to the NBS.

At ORNL the heating power was obtained by measuring (1) the heating current with a calibrated Keithley 195A Digital Multimeter (IC 038380) and (2) the voltage drop across the element with a Hewlett-Packard 3468A Multimeter (IC 501149). Measurements were taken during steady-state conditions of element resistance and power dissipation at five or more power levels. The slope of the plot of heating power minus normal measuring power versus heating resistance minus the normal resistance is linear and is termed the self-heating index (SHI) in units of ohms/watt.

4.4 Response Time Tests

4.4.1 Loop-Current Step-Response (LCSR) Method

Measurements of response time at TMI-2 and CR-3 were performed by AMS using the LCSR method described in Reference 6. Using a special response-time instrument, AMS measured the time dependence of the change of element resistance in response to a step increase in the measuring current. The response time of the PRT-thermowell assembly S/N 3670 removed from TMI-2 was measured by AMS at ORNL using both LCSR and plunge methods to verify their equivalence.

The AMS data analysis presented in Appendix II shows that the LCSR and plunge tests measure response time with a mean agreement of 6.5 ± 2.1% between the two methods. This agreement allows direct comparison of the in-situ plant test data with laboratory plunge test data.

4.4.2 Plunge Method

The response time of the PRT-thermowell assembly is defined as the time for 63.2% of the final response to a step change in external temperature. ASTM Standard E644-78 specifies the use of a bath such as shown in Figure 3, consisting of a drum of water mounted on a vertical shaft driven by an adjustable speed motor. The test item is fixed to an arm mounted on a pneumatic cylinder so the PRT-thermowell assembly can be plunged rapidly into the rotating bath. This test apparatus provides a means for establishing a known and adjustable fluid velocity past the thermometer.

The PRT temperature is monitored and is allowed to stabilize at ambient temperature before being plunged into the hot bath. A switch

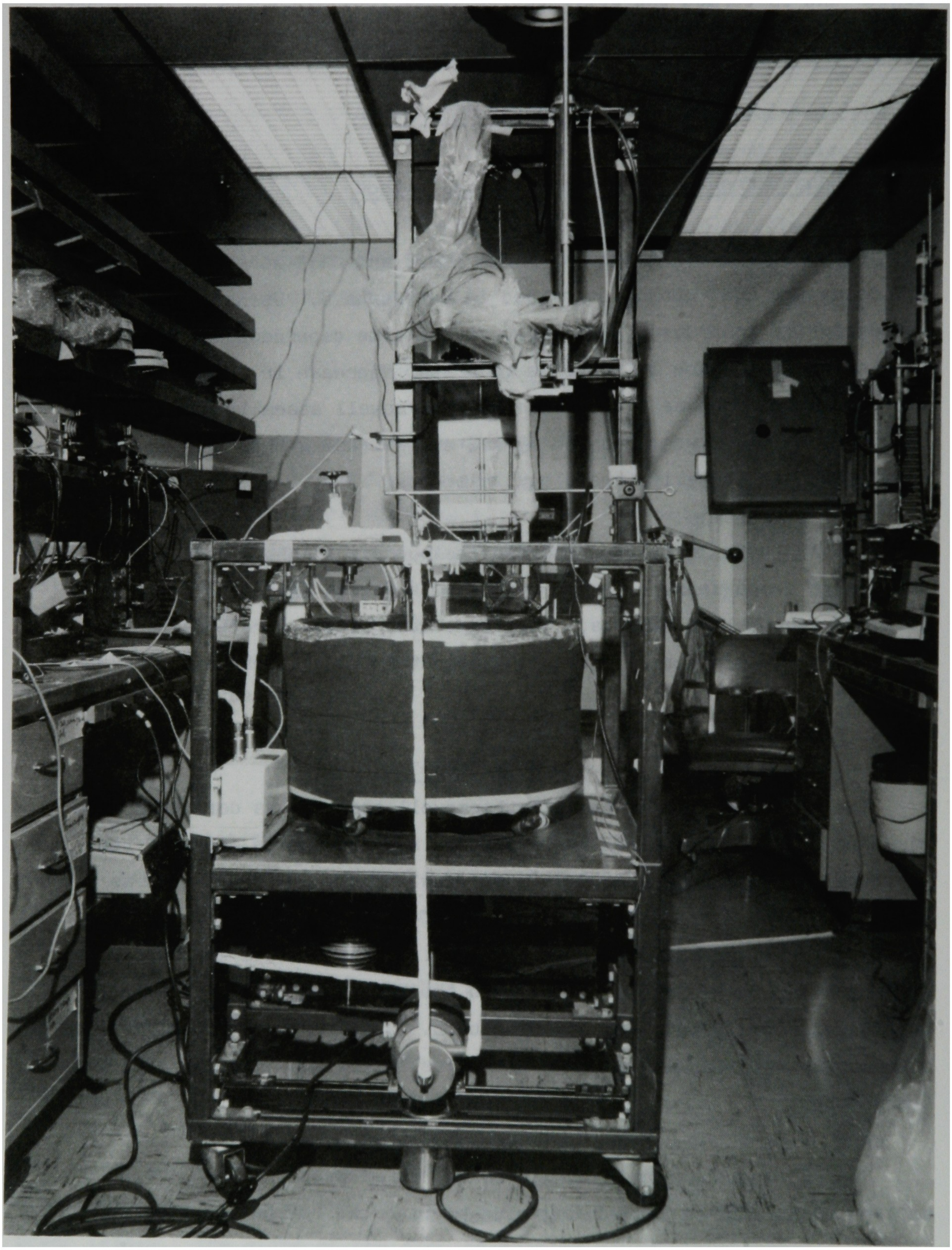

Figure 3. PRT S/N 3670 in position for response time tests under benchmark conditions.

activated by the arm starts the recorders at the instant the assembly enters the bath.

The bath temperature is controlled by circulating heated water pumped from the bath bottom on the axis of the bath into an external heater and re-entering the bath on the circumference. Baffles in the bath reduce Coriolis currents and permit radial flow only at the bottom of the tub between annular rings.

The REC test procedure, in which the response time is measured in water at 170 ± 10°F flowing at 3 fps, is generally accepted by industry as the standard benchmark condition. The REC specification (REC Dwg. No. H33551-1201, Rev. 1) for the 177 HW PRT mounted in its mating thermowell stipulates that the response time "shall be less than 6.8 s at 3 ft/s flow." Thus, to evaluate degradation of response time, the bath conditions used reproduced REC test procedure conditions.

4.4.3 Water Velocity Effects

To determine the changes in response time with water velocities other than 3 fps, the PRT was tested at water velocities from 0.13 to 3.3 fps and 170°F. The plunge test procedure for all water velocities was the same as that used at the 3-fps benchmark except for the very low flow velocities. We found that if the assembly is plunged rapidly into slowly moving water, the plunge itself will produce a relative motion in the water, thereby giving an effectively greater than recognized velocity. Therefore, the pneumatic insertion system was throttled at low bath speeds to produce a smooth but slower insertion into the bath. Response tests were also made at each water velocity using the LCSR technique, which avoids the initial flow velocity perturbation characteristic of the plunge test.

4.4.4 Temperature Effects

Response times as a function of temperature from 30°F to 170°F were measured by plunge and LCSR tests in the water bath. For higher temperatures, a stirred liquid-metal bath of an alloy of 62.5% gallium, 21.5% indium, and 16% tin (GIT) was used. This eutectic alloy is liquid above 50°F and has very good wetting properties. Because it has no known toxicity and very low vapor pressure (BP >3630°F), the bath can be used in the laboratory without special atmosphere or ventilation requirements.

Both LCSR and plunge test measurements were made in the GIT bath at the same temperatures as the water bath to establish the heat transfer relationship between the two baths. For example, at 171°F the PRT response time in the GIT bath was equal to that calculated for the water bath at 40 fps.

The response time measurements were repeated in the GIT bath as the temperature was increased. Because the PRT response time is temperature dependent, the temperature increase impressed on the PRT during the plunge test must be limited to about 20°C. To accomplish this, the PRT-thermowell assembly was heated before the plunge with clam-shell heaters mounted on tongs to allow rapid removal. When the temperature of the sensor had stabilized at the desired level, the clam shell heaters were removed just at the instant the plunge mechanism was actuated.

4.4.5 Decontamination and Calibration

The PRT-thermowell assembly S/N 3670 had gamma/beta radiation levels as high as 3 R/h upon arrival at INEL (see Appendix III). This activity consisted entirely of surface contamination. The surface deposits were reduced by decontamination efforts, but there was still too much activity to permit use of the standard oil baths specified by the REC for calibration of 177 HW PRTs. INEL therefore used a fluidized bed of heated Al_2O_3 particles and an ice bath to make a comparison calibration. An REC Model 162N20013 S/N 1471 reference PRT was placed in the fluidized particle bed, and both PRT S/N 3760 and the reference PRT were immersed to a depth of about 6 in. An activation current of 1 mA was passed in series through the sensing elements of the reference PRT and both elements of PRT S/N 3670. The resistance measurements were obtained by measuring the potential drop across the individual PRT elements using a Fluke Model 8500A Digital Multimeter.

5. RESULTS AND DISCUSSION OF IN-SITU MEASUREMENTS

The detailed results of in-situ measurements of PRTs in TMI-2 and CR-3 have been reported in Reference 6 and Appendix I. The results of those tests will be summarized here only as they relate to REC 177 HW S/N 3760, the one PRT-thermowell assembly removed from TMI-2 for calibration and response-time testing.

5.1 Sensing Element and Extension Wire Resistance

In February 1983, under shutdown isothermal conditions, all of the TMI-2 hot leg PRTs indicated temperatures of 79 to 82°F, while the cold leg PRTs indicated temperatures of 75 to 76°F. This spread is entirely reasonable for non-pumped water with natural circulation. It appears that either all of the PRTs had degraded the same amount or there were no serious calibration changes in any of the PRTs examined (i.e., no changes in element resistance).[6]

The extension wire resistances of the TMI-2 PRTs ranged from 4.8 to 6.2 Ω, while in the CR-3 reactor these resistances ranged from 4.5 to 6.4 Ω. Thus there were no significant differences in either element or extension wire resistances of the TMI-2 thermometers that could be attributed to the accident.

5.2 Insulation Resistance of TMI-2 PRTs

The resistance from elements to ground of some TMI-2 PRTs were much lower than the REC specification of 100 MΩ (see Table 1). During the insulation resistance tests with 100 V dc applied, the measured resistance drifted with time following voltage application, a symptom of moisture inside the PRT sheath or between the wire connections. The insulation resistances of these PRTs have been recorded as greater than 1000 MΩ before installation.[6] Comparison of similar PRTs in the CR-3 reactor shows (as can be seen in Note a, Table 1) that the sensors of TMI-2 sustained a large degradation of insulation resistance.

TABLE 1. INSULATION RESISTANCE OF EXTENSION CABLES AND PRTS IN TMI-2

PRT S/N	Insulation resistance[a] (MΩ)	Location
3667-1	136	Hot leg, Loop A
-2	186	
3670-1 *b	4.5	Hot leg, Loop A
-2*	0.12	
3672-1*	2.0	Hot leg, Loop B
-2	440	
3674-1	3200	Hot leg, Loop B
-2*	14	
3675-1*	6.8	Cold leg, Loop A
-2*	0.45	
3676-1	1070	Cold leg, Loop A
3679-1	205	Cold leg, Loop B
-2*	7.0	

a. Note: REC Specification for Model 177 HW requires insulation resistance (IR) to be more than 100 MΩ for the PRT without extension cables. In comparison, 15 PRTs measured at CR-3 had IRs ranging from 300 to 12,000 MΩ.

b. * Does not meet REC specification for IR.

It could not be determined during the in-situ tests at TMI-2 whether the insulation degradation was caused by moisture penetrating the PRT seal or the external wires.

5.3 Response Time and Self-Heating Index of TMI-2 and CR-3 PRTs

The 63.2% response times of the TMI-2 sensors, as measured by the LCSR method at the room temperature and uncirculated water conditions of the reactor, ranged from 23 to 35.9 s. The response times of test specimen S/N 3670 were 27.1 s and 27.4 s for Elements 1 and 2 respectively.*

Under shut-down conditions with no forced water flow and a temperature of 30°C (85°F), the CR-3 PRTs were found to have response times ranging from 19.7 to 24.6 s. The faster response times of the CR-3 reactor PRTs could be due to a combination of (1) more thermal convection in the CR-3 reactor and (2) better heat transfer by the use of Never-Seez in the CR-3 PRT thermowells.

The steady-state self-heating index (SHI) of the TMI-2 PRTs varied from 7.8 to 10.1 Ω/W with an average value of 8.7 Ω/W. PRT S/N 3670, selected for removal, had the highest SHI of the TMI-2 PRTs, 10.1 and 9.7 Ω/W for Elements 1 and 2 respectively. The highest SHI indicates that PRT S/N 3670 had the lowest surface heat transfer coefficient of the PRTs tested. In comparison, the PRTs of CR-3 had SHI values ranging from 6.3 to 7.3 Ω/W at shutdown.

The slower response times and higher SHIs of the TMI-2 PRTs as compared to those of the CR-3 indicate a lower surface heat transfer coefficient in the TMI-2 PRT-thermowell assemblies than in the CR-3 reactor. Again, this result could be due to different convective currents in the CR-3 reactor than in the TMI-2 reactor at shutdown, or to the use of Never-Seez in the CR-3 PRT thermowells.

5.4 Response Time and Self-Heating Index in CR-3 at Full Power

The purpose of testing the PRTs in CR-3 was to compare their characteristics at shutdown with those of the PRTs in TMI-2. By observing how the response time and the SHI changed when the CR-3 reactor went to operating conditions, it should be possible to predict how the TMI-2 PRTs would behave under operating conditions. The predictive plan involves two assumptions: (1) the shutdown conditions are the same, and (2) the PRTs of the two reactors have the same coolant flow rate and temperature dependence of response time and SHI.

The response times and SHIs for PRTs in the two reactors were measured by AMS during shutdown and operating conditions and are given in Table 2. The range of response times and SHIs of the PRTs in CR-3 under operating conditions may be attributed to the presence of old Never-Seez in the cold leg thermowells and fresh Never-Seez in the hot leg thermowells, resulting in an average response time of 2.5 s for the hot leg PRTs and 3.9 s for the cold leg PRTs. It should be noted that all of these response times in CR-3 were less than the 5.0-s response time limit in the plant technical specifications.

5.5 Laboratory Tests of Similar PRTS

AMS also took another approach to estimating the response time of the TMI-2 PRTs under full-power conditions. This involved comparing other 177 HW PRT thermowell assemblies tested under laboratory conditions with the measurements at TMI-2.[6] Tests were made in five different test facilities including two flow loops and three rotating water tanks.

Response-time measurements were made by AMS on four 177 HW PRTs in still water; the results are listed in Table 2. Both response times and SHIs are larger for these laboratory specimens than for the

TABLE 2. COMPARISON OF RESPONSE TIMES AND SHIs

Reactor	Condition	Response time (s)	SHI, Ω/W	Source
TMI-2	Shutdown	23 - 35.9	7.8 - 10.1	ref. 6
CR-3	Shutdown	19 - 24.6	6.3 - 7.3	ref. 6
CR-3	Operating[a]	2.3 - 4.8	5.0 - 7.0	App. I
Laboratory[b]	Still water	36.8 - 49.5	7.4 - 11.0	ref. 6

a. Water flow velocity 50 fps, temperature 550°F.
b. PRT had been removed and reinserted into thermowell many times.

PRTs in either TMI-2 or CR-3. These laboratory results are for PRTs installed in a dry thermowell where the PRTs had been removed and reinserted a number of times. The longer response times and larger SHIs are indicative of poor heat transfer between PRT and thermowell.

Tests were performed by AMS on one 177 HW PRT-thermowell assembly to obtain measurements of the response time as a function of water flow velocity, from which they predicted a response time of 12.3 s at 550°F and 50 fps flow.[6]

Tests were also made at ORNL to determine the effects of temperature and flow velocity on a 177 HW (PRT S/N 3371) and to evaluate the influence of the thermowell on the response time. The bare PRT (i.e., without thermowell) was found to have a response time that varied with water flow velocity in a manner that predicts a response time of 2.78 s at 50 fps and 170°F. Tests on this PRT in the GIT bath indicate an equivalent of water flow velocity of 38 fps for the GIT bath at 170°F.

It should be realized that at high water velocities the response time is relatively insensitive to changes in the water velocity. For example, a change of velocity from 40 fps to 80 fps would reduce the response time by only about 0.6%. Thus the GIT bath has an equivalent water velocity of more than 35 fps. Higher velocities have no significant effect on response time.

When the bare 177 HW PRT (S/N 3371) was installed in a thermowell, the response time at 170°F increased from 2.8 s to about 11 s. When Never-Seez was added to the annulus in the thermowell, the response time at 170°F dropped to 6.2 s. The response time was still temperature dependent; at 608°F the response time with Never-Seez in the annulus decreased to 4.95 s. These results indicate that the PRT response time would become shorter as the temperature of the reactor increased, not only because of changes in coolant water properties but also because of changes in the internal heat transfer properties that were not considered previously.[8]

5.6 Estimates of TMI-2 PRT Response Time at Full Power

Using the results of laboratory tests on other used laboratory specimen Model 177 HW PRTs to extrapolate the response time of the TMI-2 PRTs, AMS estimated a response time of 13 s at full temperature and flow conditions.* The estimate was made on the erroneous assumption that the laboratory PRT-thermowell assemblies were typical of those in TMI-2 and CR-3. They were not typical because their silver bushings had been worn by repeated insertion in thermowells.

A better estimate of the response time of the TMI-2 PRTs under full-power conditions can be made by assuming that they will change in the same manner from shut-down conditions as did the PRTs in the CR-3 reactor. That is, the CR-3 reactor PRTs had an average response time of 22.2 s at shutdown compared to 3.2 s at full power (Appendix I). Since the TMI-2 reactor PRTs had an average response time of 29.3 s under shut-down conditions, the at-power response time might be estimated by applying the ratio obtained at CR-3 [(3.2 s/22.2 s)(29.3 s) = 4.2 s] as the predicted response time for TMI-2 at full power. This result compares well with the 4.51-s response time extrapolated from the bench tests described in Section 6.4 using the PRT actually removed from TMI-2.

6. RESULTS AND DISCUSSION OF TESTS ON THE PRT REMOVED FROM TMI-2

Rosemount Model 177 HW PRT, tag #RC-4A-TE3, TE4 (S/N 3760), located in the hot leg of Loop A of the TMI-2 reactor, was selected as the worst-case PRT based on its low insulation resistance and high self-heating index (SHI). The PRT-thermowell assembly was removed from the reactor on April 6, 1984 and shipped to the Idaho National Engineering Laboratory (INEL) in May 1984. There it was cleaned to reduce the surface contamination (see Figure 2), which was as high as 3 R/h gamma-beta. The INEL report of these activities is included as Appendix III.

At INEL the PRT was subjected to a series of resistance and calibration tests without disturbing the PRT-thermowell mating. The PRT-thermowell assembly was also x-rayed (Figure 4) before being shipped to ORNL in August 1984.

Additional decontamination and masking of the surface (everywhere except in the region of the sensing element) were necessary in order to make response-time measurements at ORNL without contaminating the rotating tub. After response-time and self-heating index measurements were obtained, the PRT-thermowell assembly was disassembled (Figure 1).

6.1 Insulation Resistance Measurements

In-situ measurements at TMI-2 of the resistance to ground at 100 V dc applied potential indicated 4.5- and 0.12-MΩ resistance for Elements 1 and 2 respectively (Table 1). The measurements were made from the control room and therefore included the extension cables. Drifting resistances indicated moisture in the circuit, but it was not known whether the PRT seal had failed or whether the extension wire connection was wet.

Photographs taken just before the PRT was removed from the TMI-2 reactor showed that the protective conduit for the PRT extension cable for Element 2 had pulled loose from the connection head (Figure 5). Since no ferrule or insert was found for the conduit, we presume that

Figure 4. Radiograph of PRT S/N 3670 in the thermowell shows the relation of the silver bushing to the reduced section of thermowell.

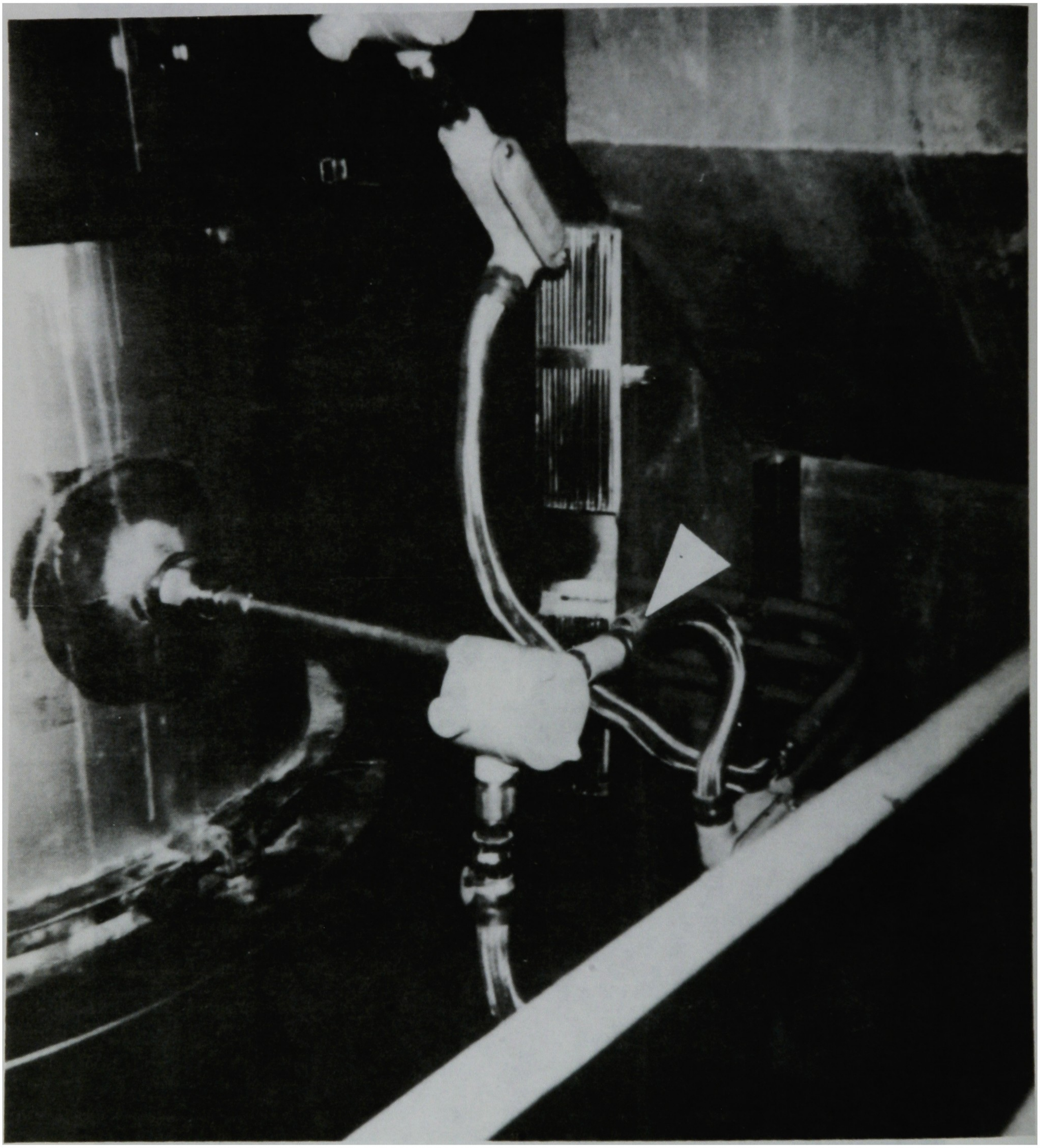

Figure 5. PRT S/N 3670 shows open conduit at the time of removal from Loop A of TMI-2.

the improperly mated conduit was pulled loose before or during the accident (perhaps by vibration) and that this allowed steam to enter the connecting head and extension cable (Figure 6), resulting in a conduction path across the connecting terminals.

When the PRT was examined at INEL without the extension cable, the insulation resistance exceeded the REC specification of 100 MΩ (Table 3). The connection head was opened for examination, was partially decontaminated, and new extension cable was added. The insulation resistance had improved still further upon arrival at ORNL.

TABLE 3. INSULATION RESISTANCE AT 100 V DC ON PRT S/N 3670

Measurement Location	Date	Element to Sheath (MΩ) (1)	Element to Sheath (MΩ) (2)
TMI-2*	1977	>1000	>1000
TMI-2*	Feb. 1983	4.5	0.12
INEL	May 1984	500	300
ORNL	Sept. 1984	1200	500

*Values include extension cables.

6.2 Calibration Verification

For calibration at elevated temperatures, TMI-2 PRT S/N 3670 was compared to a reference PRT inserted in a fluidized bed. The calibration, performed at INEL, involved five temperatures ranging from 32°F to 599°F as shown in Table 4 (see Appendix III).

The PRT showed only small deviations from its original calibration. At room temperature Element 1 showed a maximum deviation of 0.7°F and a mean deviation of 0.14°F over the entire calibration range. Element 2 had a maximum error of 0.77°F at 392°F and a mean deviation of 0.29°F

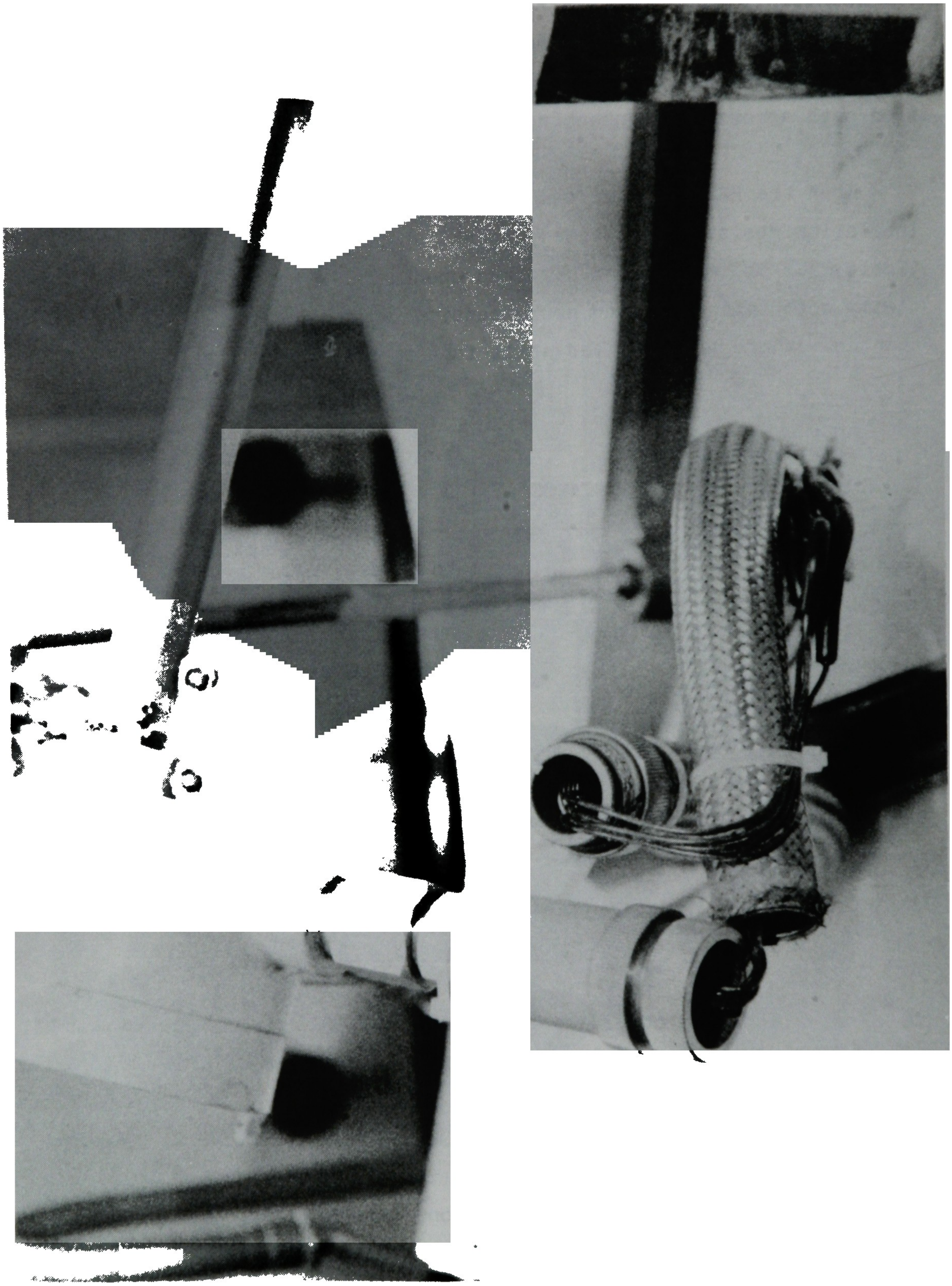

Figure 6. Cable conduit was open when the PRT assembly was removed from the TMI-2 reactor.

TABLE 4. CALIBRATION OF PRT S/N 3670 AT INEL

Target Temperature		Reference RTD*	Element 1	Element 2
	Temperatures in °C, resistances in ohms			
Freezing Point	Resistance	199.995	100.323	100.092
	Temperature	.105	.348	.015
Ambient	Resistance	216.08	108.46	108.23
	Temperature	20.360	20.746	20.440
200°F 93°C	Resistance	272.25	136.53	136.34
	Temperature	92.094	92.159	91.990
400°F 204°C	Resistance	357.70	179.40	179.09
	Temperature	204.342	204.350	203.91
600°F 316°C	Resistance	439.04	220.10	219.77
	Temperature	314.96	314.65	314.60

*Rosemount Model 162N20013 S/N 1471.

over the entire calibration range. The REC 177 HW specifications require that the PRT recalibrate to within ±0.3°F at 600°F.[10] As shown in Table 4, PRT S/N 3670 recalibrated to within about ±0.34°F, which is just outside the REC specification. The 0.34°F deviation can be attributed either to damage during the accident or to uncertainties in temperature distribution in the fluidized alumina powder bath as compared to the REC oil bath used in the original calibration. In any event, the deviation of PRT S/N 3670 from the original calibration was minimal.

Measurements of the element resistances of the TMI-2 PRTs during shut-down isothermal tests (Section 5.1) showed that all PRTs indicated about the same temperature. Thus, either all PRTs decalibrated about the same amount or none decalibrated. It follows that since PRT S/N 3670 is still in calibration, so are the other TMI-2 PRTs.

6.3 Response-Time Measurements

The variation in the response times of the PRTs measured in "still" water (Table 2) illustrates that truly "still water" conditions are difficult to achieve. Small temperature variations cause slow convection currents which have large effects on the response time. Thus, it is not possible to determine whether a given PRT with a long measured response time in still water would give a proportionately long response time under operating conditions. For this reason, only the mean values of the response times were used to estimate the expected response time at full power (Section 5.6).

Given the undefined flow conditions in the shut-down TMI-2 reactor, we must question the significance of the response times of 27.1 and 27.4 s measured for Elements 1 and 2, respectively, of PRT S/N 3670 when it was installed in the reactor. The response time of this PRT after removal from the reactor was measured at ORNL as 27 s when plunged into room-temperature still water. However, this agreement may have been fortuitous.

The mean response time of the CR-3 PRTs under shut-down conditions was 22.2 s and decreased to 3.2 s under operating conditions. It was known that the CR-3 PRTs had Never-Seez in the thermowells, whereas we now know that at least one of the TMI-2 PRTs did not. The Never-Seez in the CR-3 thermowells may account for the shorter response time at shutdown.

Both AMS and ORNL personnel measured the response times of PRT S/N 3670 at ORNL using the same plunge test equipment (shown in Figure 2), but the results were recorded using different equipment. The measured response times at 170°F for plunge tests at different water flow velocities are listed in Table 5. The bath water velocity was determined in the manner explained in Section 4.5.

TABLE 5. RESPONSE TIME OF PRT S/N 3670 WHEN PLUNGED INTO 170°F FLOWING WATER (Laboratory Tests Conducted at ORNL)

Element No.	Water Flow Rate (cm/s)	Water Flow Rate (fps)	Response Time (s) AMS	Response Time (s) ORNL
1	100.1	3.28	5.6	5.80 ± 0.01
2	100.1	3.28	5.7	5.96 ± 0.00
1	62.8	2.06	6.0	6.05 ± 0.05
2	62.8	2.06	6.1	6.13 ± 0.01
1	20.3	0.67	6.7	7.04 ± 0.09
2	20.3	0.67	7.0	7.07 ± 0.07
1	11.1	0.36	--	7.70 ± 0.01
1	4.1	0.13	--	9.84 ± 0.08
1	~ 0*		--	27.0 ± 0.3

*In this test the bath temperature was 68°F.

The response time of PRT S/N 3670 in its thermowell was measured by Rosemount Engineering to be 5.5 s in 1975 and 6.5 s in 1977. The maximum response time allowed by 1975 specifications was 8.0 s, and in 1977 the maximum allowable was 6.8 s (asserted to produce a response time of less than 5 s in water at 600°F flowing at 50 fps). The data in Table 5 show that both AMS and ORNL confirm that the response at 100 cm/s (~3 fps) still meets factory specifications and is within the range of the 1975 and 1977 measurements reported in the qualification test documents.

6.3.1 Response Time as a Function of Water Velocity

It is well known that PRT response time is a function of cooling water velocity. The problem is to relate the measured response time under laboratory test conditions to the response time under reactor operating conditions. Although this problem is eliminated by using the LCSR technique to measure the installed response under any desired operating conditions, we must address it here because the response time of

TMI-2 PRT S/N 3670 could be measured only under shut-down and laboratory conditions, not full-power operating conditions.

REC specifications relate a response time of less than 6.8 s in water at 3 fps to a response time of less than 5 s in 600°F water at 50 fps.[10] AMS found that the response time of 22.2 s in CR-3 at reactor shutdown decreased to 2.5 to 3.9 s when the reactor was operating at 550°F and 50 fps (see Section 5.4).

T. W. Kerlin of AMS has shown that the response time, τ, can be predicted by the relationship

$$\tau = C_1 + C_2/h, \tag{1}$$

where h is the surface heat transfer coefficient and C_1 and C_2 are constants at a given temperature.[11] The surface heat transfer coefficient, h, is approximately proportional to the square root of the water velocity. If the value of τ measured at various flow velocities is plotted versus the water velocity to the -0.5 power, a linear plot will be obtained (see Figure 7). The intercept at infinite velocity is equal to C_1. By calculating the value of h for a water temperature and flow rate where the value of τ was measured, the value of C_2 can be determined.

Since the measured response time has a linear relation to the flow velocity to the -0.5 power, this relationship can be used to predict the response time at flow rates other than those measured. Figure 8 shows an extended plot of the response times measured at shutdown in the TMI-2 and CR-3 reactors. If we assume that the response times under shut-down conditions are due to thermal convection currents in the reactors, then the response times which were observed could be expected if CR-3 had 0.011 fps flow and TMI-2 had 0.006 fps flow. Such convective flow rates are entirely reasonable. The difference in response times in the two situations could be caused by the presence of Never-Seez in the CR-3 thermowells and the absence of Never-Seez in the TMI-2 thermowells.

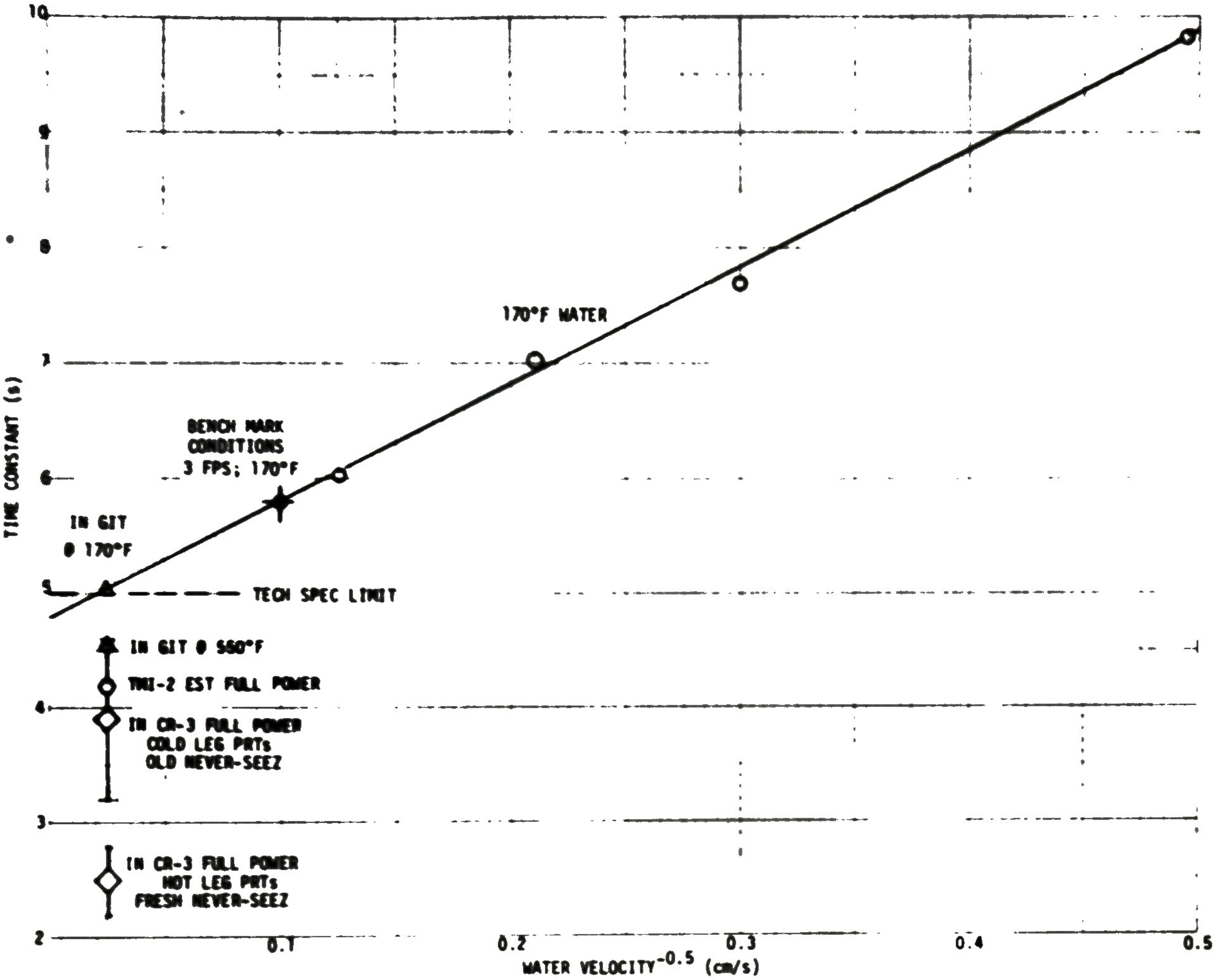

Figure 7. Time response of REC Model 177 HW in thermowell measured in laboratory tests and in TMI-2.

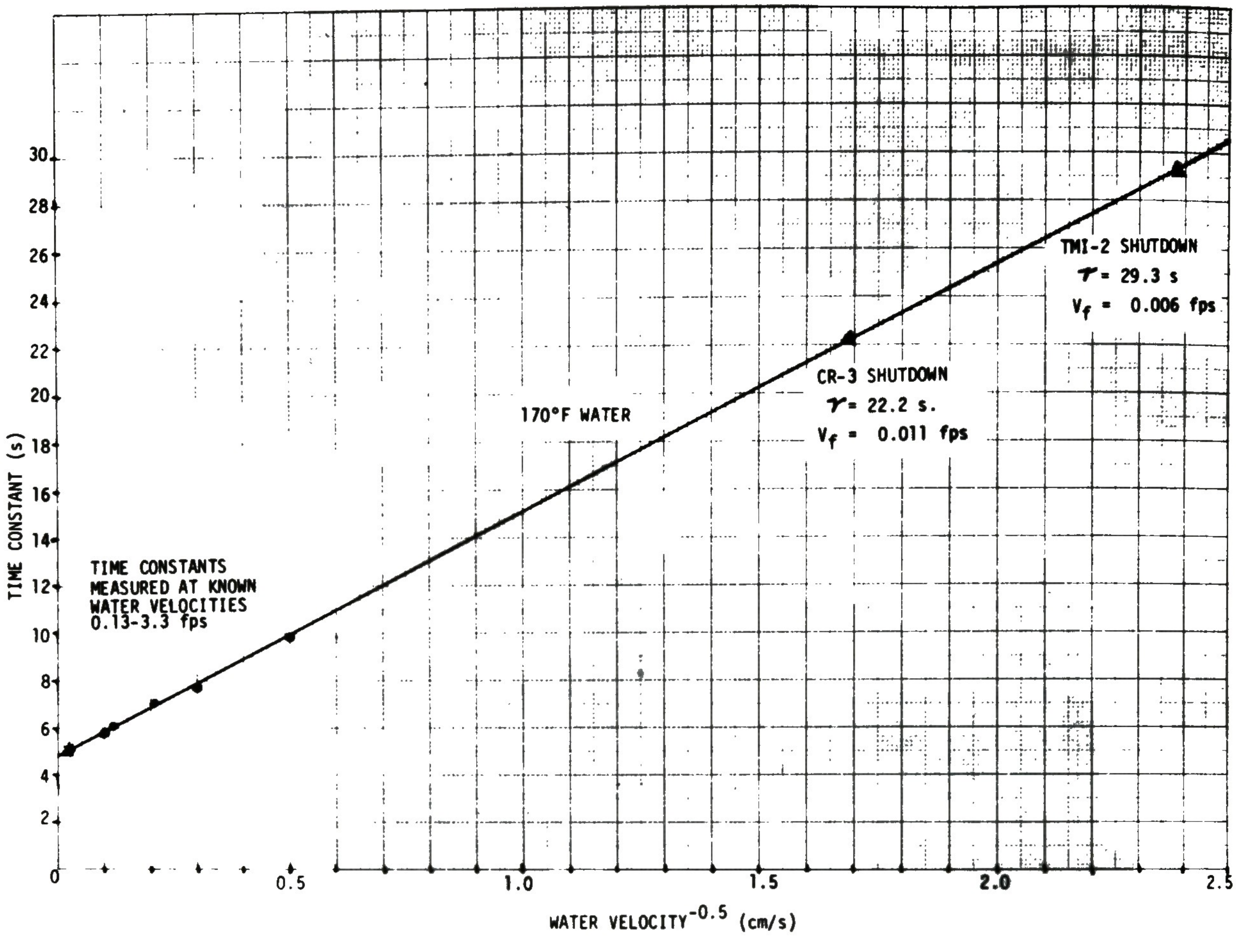

Figure 8. Estimates of still/natural circulation water flow velocities from PRT time response measured during shutdown in TMI-2 and CR-3.

The ORNL data in Table 5 were plotted in Figure 7, and from the intercept a value of $C_1 = 4.76$ s was obtained for Equation (1). Using the data and method of Reference 12, the value of h at 76°C (170°F) and 1 m/s flow was calculated to be 0.295 (W/cm²-°C) and the measured τ was 5.80 s. Thus from Equation (1)

$$C_2 = (5.80 \text{ s} - 4.76 \text{ s})\ 0.295 \text{ W/cm}^2\text{-°C} = 0.307 \text{ W-s/cm}^2\text{-°C}.$$

Substituting the values of C_1 and C_2 into Equation (1), the response time for Element 1 of PRT S/N 3670 at 76°C (170°F) can be expressed as

$$\tau = 4.76 + 0.307/h \ . \qquad (2)$$

Using the data in Table 5, independent calculations were made by AMS (Appendix II) where the water velocity, V in m/s, to the -0.6 power was plotted versus τ, yielding, for 70°C water, the relations

$$\text{Element 1, } \tau = 5 + 0.7\ V^{-0.6} \qquad (3)$$

$$\text{Element 2, } \tau = 5 + 0.8\ V^{-0.6} \ . \qquad (4)$$

There is some question whether the heat transfer coefficient is best represented by velocity to the -0.6 power or the -0.5 power. AMS has recently concluded that the -0.5 value is a better representation. Either the AMS or the ORNL analysis predicts a PRT response time of about 5 s in water at 76°C (170°F) at a flow rate of 40 fps or higher. These analyses, however, neglect the influence of temperature.

6.3.2 Response Time as Function of Temperature

The response time of PRTs has been shown to depend on the coolant temperature.[8] The response time of PRT-thermowell assembly S/N 3670 was measured in a stirred, heated GIT bath as described in Section 4.7. The variation of the response time with temperature is shown in Table 6 and illustrated in Figure 9. The measurements, as shown by the small deviations of repeated tests, indicate that slight variations in the temperature difference between the assembly and the GIT bath (about 20°F) were not important.

TABLE 6. RESPONSE TIME OF TMI-2 PRT S/N 3670 PLUNGED INTO STIRRED LIQUID METAL (GIT)

Number of tests	Temperature* (°F)	Mean Value Response Time (s)	Deviation $1\ \sigma$ (s)
4	142	5.09	0.01
3	169	5.05	0.02
2	360	4.66	0.00
3	293	4.74	0.02
4	493	4.58	0.05
3	585	4.53	0.03

*ΔT is approximately 20°F.

6.4 Calculation of Response Time at Full Power

The measured response time of the assembly in a GIT bath at 169°F was 5.05 s, and this result, evaluated in terms of response time as a function of water velocity (see Figure 7), indicates that the response time corresponds to a water velocity of 50 fps. The measurement uncertainty of response time is about ±1%, and thus a velocity range of 40 to 80 fps is probable.

From Table 6 and Figure 9, the response time is seen to decrease as the temperature increases. If the GIT bath has the equivalent surface heat transfer of water at 40 to 80 fps, then at 585°F the response time would be 4.5 s. The response time at 550°F is obtained from Figure 9 and shown on Figure 7 for comparison to the measured response time in the CR-3 reactor.

We can directly relate heat transfer in GIT at 170°F to a water velocity at 170°F, but we know that water properties change with

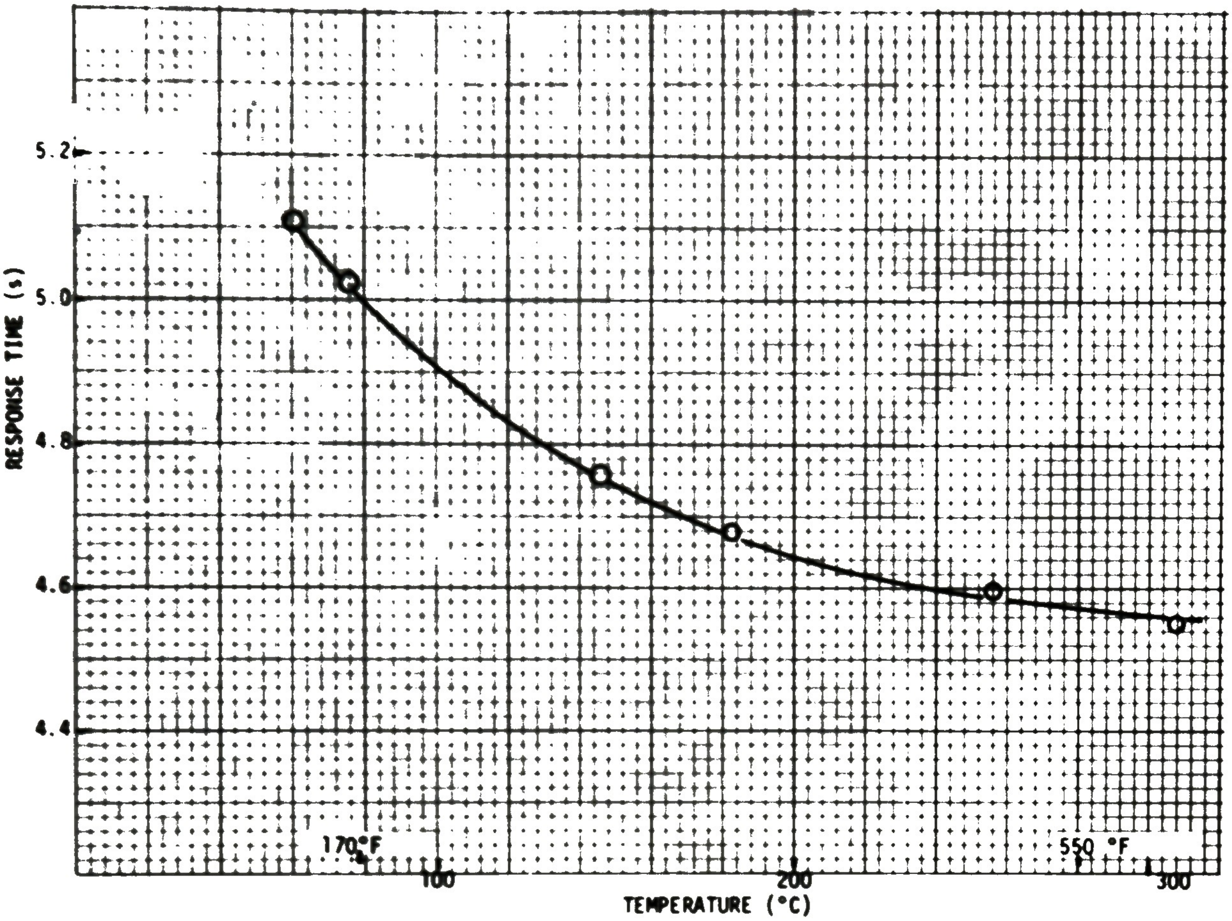

Figure 9. Temperature dependence of response time of REC Model 177 HW PRT in thermowell when measured in GIT. (Equivalent to water at 170°F.)

temperature. Therefore, the measured response time of 4.5 s in GIT at 585°F cannot be directly related to the expected response time in water at the same temperature. However, by using Equation (1), where

$$\tau = C_1 + C_2/h \tag{5}$$

and assuming that the value of C_2 is not temperature dependent but C_1 and h are temperature dependent, we can estimate the response time at elevated temperatures. In Equation (2), the value of C_2 for the PRT assembly was calculated to be 0.307 W-s/cm²-°C. We measured the value of τ in GIT at 307°C (585°F) to be 4.53 s (Table 6). Thus

$$C_1 = \tau - C_2/h = 4.53 - 0.307/h \; . \tag{6}$$

At 80 fps flow rate and 307°C (585°F), the heat transfer coefficient, h, of water is calculated to be 1.76 W/cm²-°C. Then C_1 can be calculated (Equation 6) to be 4.36 s, and so

$$\tau = 4.36 + 0.307/1.76 = 4.53 \text{ s} \tag{7}$$

for the PRT S/N 3670 under reactor conditions of 307°C (585°F) coolant temperature and 80 fps flow rate.

If, for example, the coolant water were flowing at 50 fps as in CR-3, the value of h is calculated to be 1.22 W/cm²-°C, and from Equation (5), using the values of C_1 and C_2 as shown in Equation (6), we find

$$\tau = 4.36 + 0.307/1.22 = 4.61 \text{ s} \; . \tag{8}$$

Thus, changing the flow from 80 to 50 fps is expected to change the response time only from 4.53 to 4.61 s. It is interesting to note that the simple ratio method given in Section 5.6, which compared response times in still water for TMI-2 and CR-3, predicted an average response time of 4.2 s for the TMI-2 PRTs at reactor operating conditions, as shown by the hexagon marker in Figure 7.

6.5 Self-Heating Index Measurements

One of the reasons for selecting the PRT S/N 3670 assembly as a worst case was that it had the highest SHI of the installed PRTs. A high SHI indicates poor surface heat transfer between the element and the coolant and thus is generally associated with a long response time (Table 2).

The SHIs for Elements 1 and 2 of PRT S/N 3670 were 10.1 and 9.7 Ω/W, respectively, while the other TMI PRTs had SHIs ranging from 7.8 to 9.3 Ω/W.[*] The CR-3 PRTs had SHIs ranging from 6.3 to 7.3 Ω/W under shut-down conditions. The smaller SHIs and shorter response times of the CR-3 PRTs, as compared to those of TMI-2 (see Figures 7, 8), indicate better surface heat transfer conditions for the CR-3 PRTs. Since the SHI is not as sensitive to surface flow as is the response time (Table 2), more significance was placed on the high SHI of PRT S/N 3670 than on the median response time of the PRT in still water.

In the still-water laboratory test the SHI for PRT S/N 3670 was 10.9 and 10.5 Ω/W for Elements 1 and 2, respectively, which is in reasonable agreement with the in-situ tests in view of the undefined circulation currents in the TMI-2 reactor. Both elements showed an 8% increase in SHI when the PRT was tested in still water laboratory conditions as compared to the in-situ tests at TMI-2.

6.6 PRT-Thermowell Disassembly

The PRT S/N 3670 was removed from its mated thermowell in a fume hood. The silver bushing was, as shown in Figure 1, bright and clean. There was no powder residue in the thermowell. We concluded (based on the lack of discoloration on the sheath) that the PRT had not been seriously overheated. We also concluded that Never-Seez had not been used for this particular thermowell at any time during the service life of the PRT and, on the assumption that other PRTs in TMI-2 were installed using the same procedure, inferred that probably none of the PRTs in TMI had Never-Seez in their thermowells.

7. CONCLUSIONS

The PRT test results lead us to conclude the following:

1. The low insulation resistance exhibited by many of the PRTs is attributable to failure of the cable conduits or the seals of the connecting heads. (All but two of the TMI PRTs showed evidence of moisture.) After PRT S/N 3670 was removed from the reactor, the insulation resistance increased to a value that exceeds factory specifications with the extension cable removed, indicating that the sheath seal was still intact.

2. The calibration of PRT S/N 3670 was not changed significantly by the accident. Since the in-situ tests showed the same element resistance for all PRTs in TMI-2 during nearly isothermal conditions, it is likely that none of the PRTs suffered a significant loss of calibration.

3. The response time of PRT S/N 3670 under benchmark conditions lies between the two sets of measurements reported in the original factory certifications. Therefore, there appears to be no degradation of response time in this PRT.

4. From laboratory measurements of response time at different temperatures and coolant flow rates, the response time of PRT S/N 3670 was calculated to be 4.5 ± 0.1 s under TMI-2 operating conditions. This value is even less than the 5 s required by the TMI-2 plant technical specifications.

5. The TMI-2 PRT S/N 3670 met the technical specification response time requirement without the use of Never-Seez in the thermowell.

6. The self-heating index showed that PRT S/N 3670 had a poorer heat transfer to the surrounding reactor coolant water than did the other PRTs. This result provides an indication, but

not proof, that the other TMI-2 PRTs probably have shorter response times under benchmark conditions than the one PRT that was removed.

8. RECOMMENDATIONS

The only failure mechanism in PRTs that resulted from the LOCA in TMI-2 apparently was caused by steam entering the wiring housings, condensing there, and shunting the signals to an unknown extent. Consequently, it would seem advisable to require that signal cable conduits and connecting housings of PRTs for nuclear plants be (1) tested for ability to withstand the expected vibrations and (2) verified to be hermetically sealed after installation.

REFERENCES

1. Field Task Proposal, "Temperature Sensor Diagnostics for TMI-2," R. L. Shepard to R. K. Kibbe, May 1, 1980.

2. Analysis of Three Mile Island - Unit 2 Accident, NSAC-80-1, NSAC-1, Revised March 1980.

3. Rosemount Engineering Company, "Manual for Model 177 HW Reactor Coolant Temperature Sensor Assembly," REC Manual 127311E, Rev. A.

4. Never-Seez, Pure Nickel Special, Nuclear Grade, Cat #NS-165 is an anti-seize compound made by the Boslik Division of the Emhart Corp. and described in "Material Safety Data Sheet on Never-Seez Lubricating Compound-Pure Nickel Special," Section III, Physical Data.

5. H. W. Hashemian, Effect of Never-Seez Degradation on Time Constant of a Rosemount Model 177 HW RTD, Analysis and Measurement Services Corp., AMS-BC8201R1, March 17, 1983.

6. H. M. Hashemian et al., Status of the TMI-2 Primary RTDs During and After the Accident, Report ORNL-AMS 8304R1, September 1983.

7. T. W. Kerlin et al., "Response of Installed Temperature Sensors," in Temperature, Its Measurement and Control in Science and Industry, Vol. 5, pp. 1357-66, Amer. Inst. Phys., 1982.

8. R. M. Carroll and R. L. Shepard, "The Effects of Temperature on The Response Time of Thermocouples and Resistance Thermometers," Proceedings of the Industrial Temperature Measurement Symposium, Knoxville, Tennessee, September 1984.

9. R. M. Carroll and R. L. Shepard, Measurements of the Response Times of Thermocouples and Resistance Thermometers using an In-Situ Method, ORNL-TM-4573 (1976).

10. Rosemount Engineering Company, "Certified Configuration Drawing, Sensor, Temperature, Platinum Resistance Type," Drawing and Part No. H33551-1201, Rev. A, Code I.D. #04274, Approved May 2, 1975.

11. T. W. Kerlin, Estimation of Sensor Response Using Tests in Flowing Water, Interim Report, Contract #Carbide Sub 7685PA535 PASQUA, October 6, 1983.

12. F. D. Werner, "Time Constant and Self-Heating Effect for Temperature Sensors in Moving Fluids," Rosemount Engineering Company Bulletin 106017, Appendix C, Rev. A.

APPENDIX I

RESPONSE TIME TESTING OF CRYSTAL RIVER RTDs AT FULL POWER

Report AMS-OR8401RO

H. M. Hashemian

June 11, 1984

ANALYSIS & MEASUREMENT SERVICES

4706 PAPERMILL ROAD / KNOXVILLE, TN 37919 / (615) 588 9709

Report # AMS-OR8401R0

Interim Report

By: Hashem M. Hashemian

Date: June 11, 1984

Re: Response Time Testing of Crystal River RTDs at Full Power.

Contract #: 62X-16958

Summary

In-situ response time tests were performed on eight primary coolant RTDs at Crystal River nuclear power plant at normal operating conditions. These tests were performed April 12 and 13, 1984. The results are given in this report. The main conclusion is that the in-service time constant of the RTDs are less than 5.0 seconds as required in the technical specifications of most B & W plants.

The work reported herein was conducted as a part of the program to study the response behavior of the primary RTDs at Three Mile Island unit 2 nuclear station. The program outline and previous results were presented earlier in report number

ORNL-AMS8304R1 entitled "Status of TMI-2 Primary RTDs During and After the Accident."(1)

1. Description of the Tests

Eight primary coolant RTDs were tested in this study. A listing of these RTDs is given in Table 1. All RTDs were tested as installed in their thermowells with the plant operating at full power. The hot leg RTDs are new sensors that were installed in 1983 with fresh NEVER-SEEZ. The cold leg RTDs are old sensors with old NEVER-SEEZ in their thermowells.

The following tests were performed on each RTD:

1. Loop Current Step Response (LCSR) Test.
2. Self Heating Test.

The LCSR test provided the in-service time constant of the RTDs and the self heating tests gave the self heating indices. Typical plots of raw data from LCSR and self heating tests are shown in Figures 1 and 2. A heating current of about 50 milliamperes was used to perform the LCSR tests. The LCSR test was repeated twenty times on each RTD. The twenty transients were averaged to obtain a smooth LCSR curve which was then analyzed to identify the time constant of the RTD tested. For the self heating tests, measurements were made at five different current levels ranging from about 10 to about 50 milliamperes.

TABLE 1

Crystal River RTDs

Tested in This Study

Item	Tag Number	Installation
1	RC-4A-TE2	Hot leg loop A
2	RC-4A-TE3	Hot leg loop A
3	RC-4B-TE2	Hot leg loop B
4	RC-4B-TE3	Hot leg loop B
5	RC-5A-TE2	Cold leg loop A
6	RC-5A-TE4	Cold leg loop A
7	RC-5B-TE2	Cold leg loop B
8	RC-5B-TE4	Cold leg loop B

All RTDs are Rosemount Model 177HW installed in Rosemount Model 177-463 thermowells.

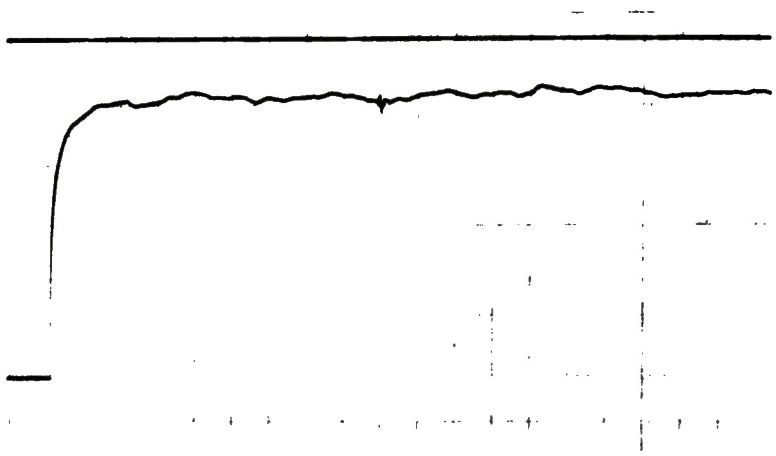

Figure 1: A Typical LCSR Test Transient for a Crystal River RTD Tested At Full Power. Chart Speed: 1 mm/sec.

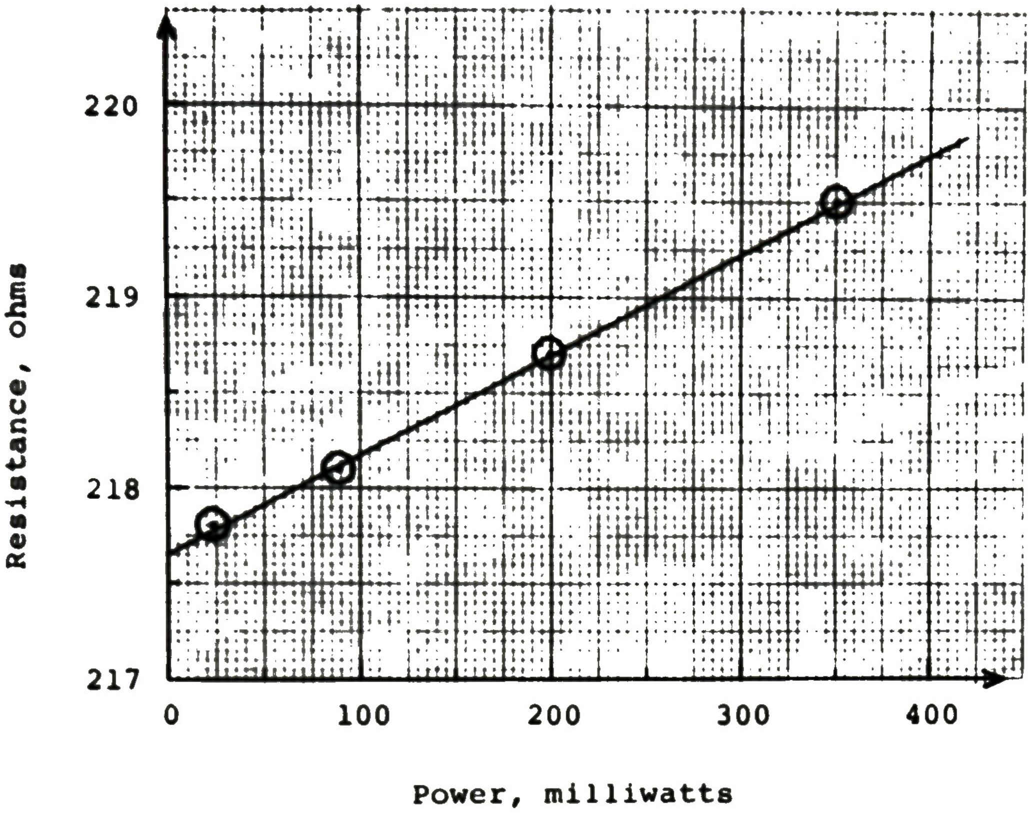

Figure 2: A Typical Self Heating Curve for a Crystal River RTD Tested at Full Power.

2. Test Results

The time constants are given in Table 2 and the self heating indices are presented in Table 3. The average time constant of the hot leg RTDs is 2.5 seconds and 3.9 seconds for the cold leg RTDs. This is consistent with the fact that the hot leg RTDs are new and have fresh NEVER-SEEZ while the cold RTDs are old and have old NEVER-SEEZ in their thermowells.

Note that the time constants are less than 5.0 seconds which is the limit for the time constant of safety system RTD elements in B & W plants.

TABLE 2

In-Service Time Constants of Crystal

River RTDs

Item	Tag Number	Time Constant (Sec.)
1	RC-4A-TE2	2.3
2	RC-4A-TE3	2.9
3	RC-4B-TE2	2.3
4	RC-4B-TE3	2.6
5	RC-5A-TE2	3.3
6	RC-5A-TE4	4.1
7	RC-5B-TE2	3.5
8	RC-5B-TE4	4.8

Above time constants were obtained from analysis of LCSR data. Twenty data sets were sampled then averaged for each RTD. A sampling rate of 20 milliseconds was used for all RTDs.

Items 1-4	Hot Leg RTDs, with fresh Never-Seez 599°F Water at 67.5 fps	2.53 ± 0.29 sec.
Items 5-8	Cold Leg RTDs, with old Never-Seez 557°F Water at 52 fps	3.92 ± 0.67 sec.

TABLE 3

Self Heating Indices for Crystal River RTDs at Full Operating Conditions

Item	Tag Number	Self Heating Index (ohms/watt)
1	RC-4A-TE2	5.9
2	RC-4A-TE3	5.5
3	RC-4B-TE2	5.6
4	RC-4B-TE3	6.6
5	RC-5A-TE2	5.0
6	RC-5A-TE4	5.2
7	RC-5B-TE2	7.0
8	RC-5B-TE4	5.2

Acknowledgment

The cooperation of Florida Power Corporation is gratefully acknowledged. Mr. E. Morris Howard, Crystal River Plant Manager, approved the testing of the plant RTDs and Mr. Jack Peebles of Crystal River I&C Division coordinated the on-site data acquisition work.

References

1. H. M. Hashemian, et. al., "Status of TMI-2 Primary RTDs During and After the Accident", Report# ORNL-AMS8301R1 Vol. 1 and 2, Analysis and Measurement Services Corporation, September 1983.

APPENDIX II

LABORATORY TESTING OF THE ROSEMOUNT MODEL 177 HW RTD REMOVED FROM TMI-2

H. M. Hashemian

November 8, 1984

ANALYSIS &
MEASUREMENT SERVICES

4706 PAPERMILL ROAD / KNOXVILLE, TN 37919 / (615) 588-9709

Interim Report

To: R. L. Shepard

From: H. M. Hashemian

Date: November 8, 1984

Subject: Laboratory Testing of the Rosemount Model 177HW RTD Removed From TMI-2.

Laboratory response time tests were performed at ORNL on one model 177HW RTD/Thermowell assembly. This is a dual element, 100 ohm, well-type, platinum resistance thermometer manufactured by Rosemount Engineering Co. This type RTD is used in most PWRs manufactured by B & W. The RTD/Thermowell assembly was removed from TMI-2 for laboratory examination. AMS performed plunge tests and LCSR tests on each element of the RTD at three different flow rates. A rotating tank of water at approximately 70°C was used as the response time test bath.

The purpose of this work was to identify the time constant of the RTD in laboratory condition, identify the changes in time constant with flow rate, and to verify that the LCSR method is valid for testing this RTD.

The results are given in Table 1. These results indicate that the laboratory time constant of this RTD is approximately 5.7 seconds in water at about 70°C flowing at approximately 1 meter/second. (Rosemount Engineering Company uses the same test environment and procedure for identifying the time constant of Industrial RTDs.) In addition, the results show that the Loop Current Step Response Method is valid for response time testing of this RTD and the accuracy is better than 10 percent. The effect of flow rate on time constant is also apparent in the results. The time constant increases as the flow is decreased. Based on the limited response vs. flow data in Table 2, the following time constant (T) vs. flow rate (U) were obtained for the two elements of the RTD in water at 70°C.

Element #1 $$T = 5 + 0.7U^{-0.6} \qquad (1)$$

Element #2 $$T = 5 + 0.8U^{-0.6} \qquad (2)$$

Above equations show that the time constant of this RTD at 70°C approaches 5 seconds at high flow rates.

Additional background data are presented in tables 2 and 3 as attached to this report.

TABLE 1

Response Time Test Results for the 177HW RTD

Removed From TMI-2

(RTD S/N = 3670)

Flow Rate (Meter/Second)	RTD Element#	Time Constant (Sec.) Plunge	Time Constant (Sec.) LCSR	Agreement
1.0	1	5.6	5.3	-6
	2	5.7	6.0	+5
0.6	1	6.0	5.7	-5
	2	6.1	5.5	-11
0.2	1	6.7	6.4	-5
	2	7.0	7.5	+7

Note: The LCSR results were obtained by analysis of LCSR data using the AMS Standard Analysis Code.

TABLE 2

Response Time Data for 177HW RTD

Data Source	Time Constant (Sec.) 3 fps	Operating	NEVER-SEEZ
Rosemount Engineering Co.	8.0	4.6	?
AMS/Removed From TMI	5.7	5.0	?
CR-3	-	2.3 to 4.8	Yes
AMS/Bailey	14	12	No
	8.0	6.5	Yes
OConee	-	6.6	?

Reference: Report # ORNL-AMS8304R1 "Status of TMI-2 Primary RTDs During and After the Accident. VOL. 1."

Page 4

TIME RESPONSE OF ROSEMOUNT 177HW RESISTANCE THERMOMETERS

TABLE 3

	INSTALLATION				FLUID CONDITION		MEASURED AT	DATA SOURCE	RESPONSE
	BARE	IN-WELL	CONDITION	NEVER-SEEZ	FLOW VEL fps	TEMPERATURE °F			sec
1	-	X	-	-	-	-	-	TMI-2 FSAR	5.0
2	-	X	-	-	80	-	-	RMT DWG H33551	4
	-	X	-	-	3	-	-	-1201	8
3	-	X	-	-	50	600	-	RMT SPEC DWG	5.0
	-	X	-	-	3	170	-	177HW	6.8
4	-	X	new	-	Cold Leg;operating		Oconee 3	EPRI-NP834-1	6.59
5	-	X	old	No	3	70	AMS	AMS/Bailey	13.8-14.8
	-	X	old	Yes	3	70	AMS	AMS/Bailey	7.8- 8.1
	X	-	old	-	3	70	AMS	AMS/Bailey	6.8- 7.3
								ORNL-AMS Report	
6	-	X	old	No	stagnant	70	Lab	Table 12.4	36.8-49.5
	-	X	P.A.	?	nat.circ.	70	TMI-2	" "	23 -35.9
	-	X	new	Yes	stagnant	83	CR-3	Table 11.3	19.7-24.6
	-	X	new	Yes	sl.moving	83	CR-3	Table 11.4	9.6-11.7
7	-	X	old	-	50	70	est	Table 12.5	12.5-13.2
	-	X	old	-	3	70	lab	" "	13.7-14.4
8	-	X	old	-	50	550	est	Table 12.6	12.3-13.0
	-	X	old	-	3	550	est	" "	13.0-13.8

RLS:ORNL. 2/28/84

APPENDIX III

PRELIMINARY REPORT, EXAMINATION AND TESTING OF TMI-2 RESISTANCE TEMPERATURE DETECTOR (RTD) RC-4A-TE3/RC-4A-TE4 AND THERMOWELL ASSEMBLY

R. C. STRAHM
Idaho National Engineering Laboratory

May 28, 1985

TEST REPORT
TEST, EVALUATION & ASSEMBLY BRANCH
TEST & EVALUATION SECTION

TITLE:

Preliminary Report, Examination and Testing of TMI-2 Resistance Temperature Detector (RTD) RC-4A-TE3/RC-4A-TE4

REPORT NO:

TR 020

DATE:

May 28, 1985

PROJECT:

TMI-2

PREPARED BY:

R C Strahm

R. C. Strahm

APPROVED BY:

GA Thorsen

G. A. Thorsen

OTHER APPROVALS:

N/A

WORK AUTHORIZATION NUMBER:

751302010

WORK REQUESTOR:

R. D. Meininger

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Initial Exaimination	1
Calibration Checks	2
X-rays	2
Conclusion	3

DISTRIBUTION:

R. H. Beers
R. D. Meininger
G. A. Thorsen

PRELIMINARY REPORT

EXAMINATION AND TESTING OF

TMI-2 RESISTANCE TEMPERATURE DETECTOR (RTD)

RC-4A-TE3/RC-4A-TE4 AND THERMOWELL ASSEMBLY

INTRODUCTION

This report discusses the examination and testing of platinum Resistance Temperature Detector (RTD) RC-4A-TE3/RC-4A-TE4 which, complete with its thermowell, was removed from the TMI-2 reactor primary coolant system on April 6, 1984. The thermowell/RTD assembly was shipped to Idaho National Engineering Laboratory (INEL) in May, 1984. Preliminary, cursory examination and resistance measurements were made.

The assembly was then subjected to a radioactive material examination, including gamma scans and particle removal. A separate report will be issued on this examination by others.

The assembly was then further cleaned of radioactive contamination and subjected to further electrical resistance tests and a series of calibration checks. It was then X-rayed and repackaged for shipment to ORNL where it will be further tested for its transient response characteristics.

The RTD/thermowell remained intact during all of these tests, i.e., the RTD was not removed from the thermowell.

DESCRIPTION OF ASSEMBLY

The RTD/thermowell assembly is a dual element platinum resistance detector manufactured by Rosemount, Inc. Factory specifications are given in Table 1. The assembly was removed from the "A" steam generator Candy Cane.

Reference 1 provides greater description of this and the other RTD's in TMI-2, and discusses in-situ test results.

INITIAL EXAMINATION

The RTD/thermowell assembly was unpacked and placed in a fume hood at the INEL Test Reactor Area (TRA). Several photographs were taken. See Figures 1 thru 5.

Note the loose conduit fitting which appears to have been pulled apart. Photographs taken at TMI just prior to removal of the assembly show that this fitting was already open at that time. This conduit carries the wire for element No. 2 (RC-4A-TE4).

INITIAL EXAMINATION (continued)

The serial number of the RTD was verified as being SN 3670.

A radiation survey was conducted except that no smears were taken on the probe itself. The direct gamma/beta radiation was as high as 3 R/h. Random swipes revealed contamination levels as shown in Figure 6.

Wiring in the connector head was as shown in Figures 7a and 7b.

Resistance measurements were made from the ends of the cut-off copper-colored extension wires. A Hewlett Packard Model 4329A was used for insulation resistance measurements in both forward and reverse polarity modes. The case of the connection head was used as the ground or return side.

A Fluke model 8500A was used in the 4-wire configuration for making the sensor resistance measurements. A recently calibrated reference RTD was placed in the fume hood to monitor the air temperature and its resistance was also recorded.

The results of these initial measurements are given in Table 2.

The assembly was then turned over to others for radionuclide examination and deposition removal. The results of this effort will be the subject of another report. During this effort the assembly was partially decontaminated. The assembly was then returned for further tests.

CALIBRATION CHECKS

The assembly was further decontaminated and then subjected to calibration tests. The media for the elevated temperature was an alumina fluidized bed. The test system was as shown in Figure 8.

A reference RTD was placed in the fluidized bed with the TMI RTD. Both were immersed in the media to a depth of about six (6) inches. The results of these tests are as shown in Table 3.

X-RAYS

X-rays were then made of the assembly. The X-rays showed that the RTD tip was in intimate contact with the thermowell inner diameter.

CONCLUSIONS

The RTD appears to be capable of providing good temperature measurements. No significant degradation was found.

The insulation resistance, while not as high as desired, was not as low as found during in-situ tests. This is probably because the low readings were caused by moisture which found its way into the RTD wiring through the loose conduit noted earlier in this report and which has subsequently dried out.

Further tests and examinations are to be performed at Oak Ridge National Laboratory to evaluate the response time characteristics of the assembly.

1. H. M. Hashemian, et al, Status of TMI-2 Primary RTD's During and After The Accident Vol's 1 & 2. ORNL---AMS8304R1, September 1983.

TABLE 1

FACTORY SPECIFICATIONS OF ROSEMOUNT MODEL 177HW RTD

ITEM	DESCRIPTION	SPECIFICATION
1.	Rosemount Part Number For Temperature Sensor Assembly	177-463
2.	Temperature Range	0°F to 670°F
3.	Sensing Elements*	Fully annealed, reference grade, .0007" platinum wire.
4.	Ice Point Resistance	100±1 ohms
5.	Material	304 SST
6.	Insulation Resistance	At room temperature and with dry external surface, the insulation resistance between each terminal lead and the sensor case shall exceed 100 megohms when measured at 100 VDC.

*Element 1 is RC-4A-TE3
Element 2 is RC-4A-TE4

TABLE 2

INITIAL RESISTANCE MEASUREMENTS

	INSULATION RESISTANCE @ 100 VDC (OHMS)	ELEMENT RESISTANCE (OHMS)	TEMPERATURE (FROM TABLE) °C
Element 1 RC-4A-TE3 Red Stripe & White Wires	FWD Polarity: $5x10^8$ REV Polarity: $5x10^8$	109.902	24.39
Element 2 RC-4A-TE4 Black Stripe & Green Stripe Wires	FWD Polarity: $3x10^8$ REV Polarity: $3x10^8$	109.893	24.63
Reference RTD Rosemount Mod 134FW60 S/N 14573	N/A	273.54	25.25

TABLE 3

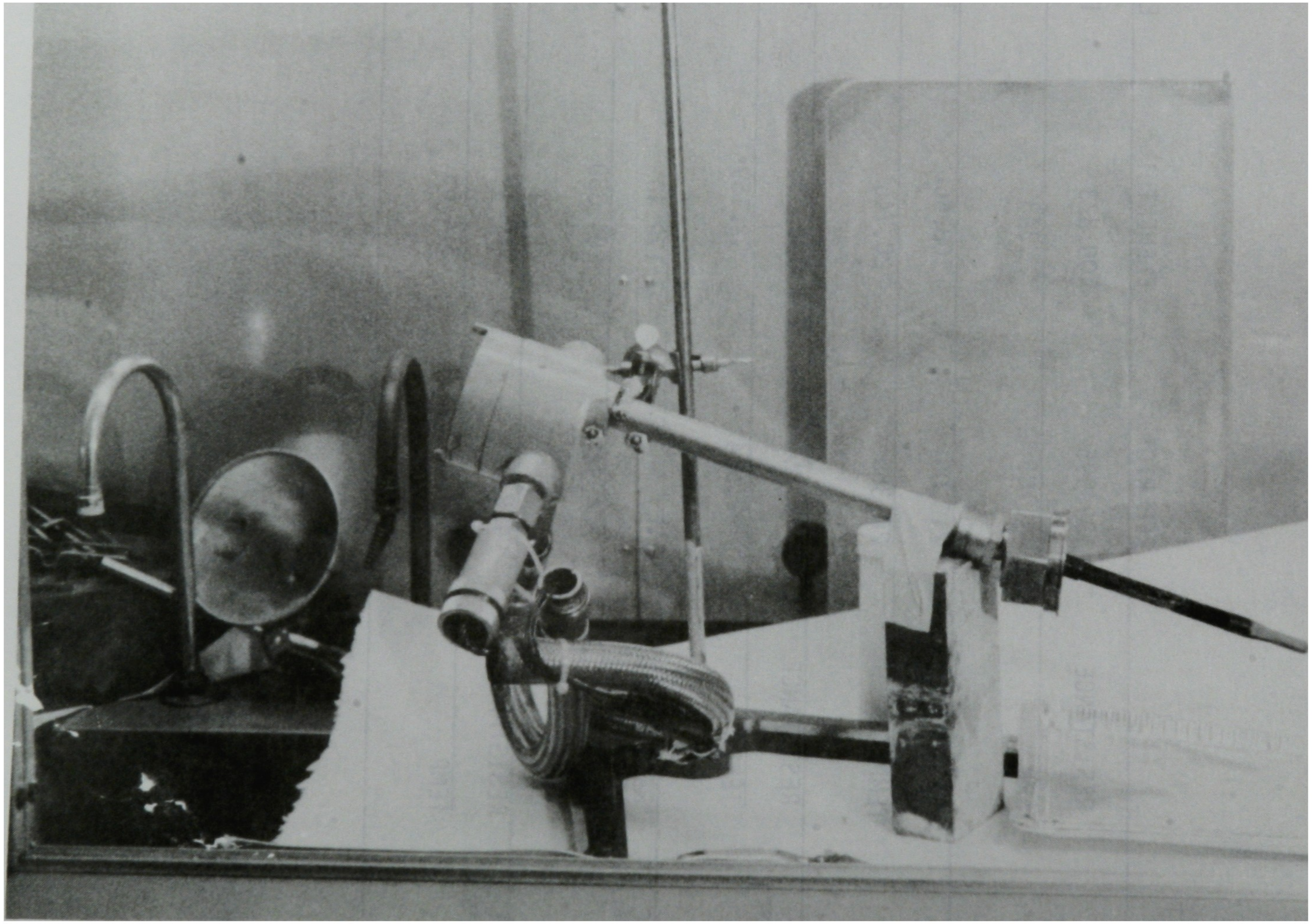
CALIBRATION CHECKS

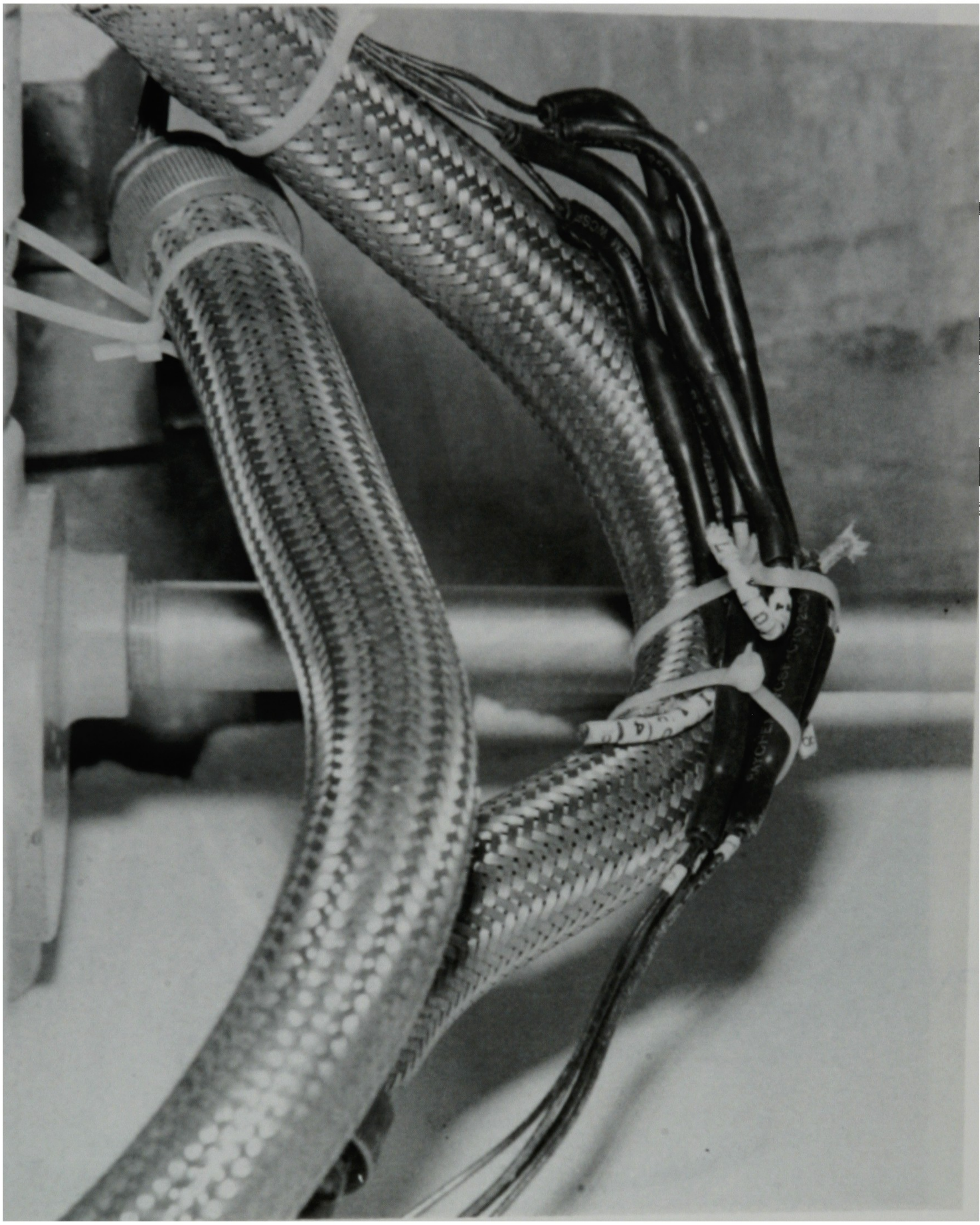
TEMPERATURES IN °C, RESISTANCES IN OHMS

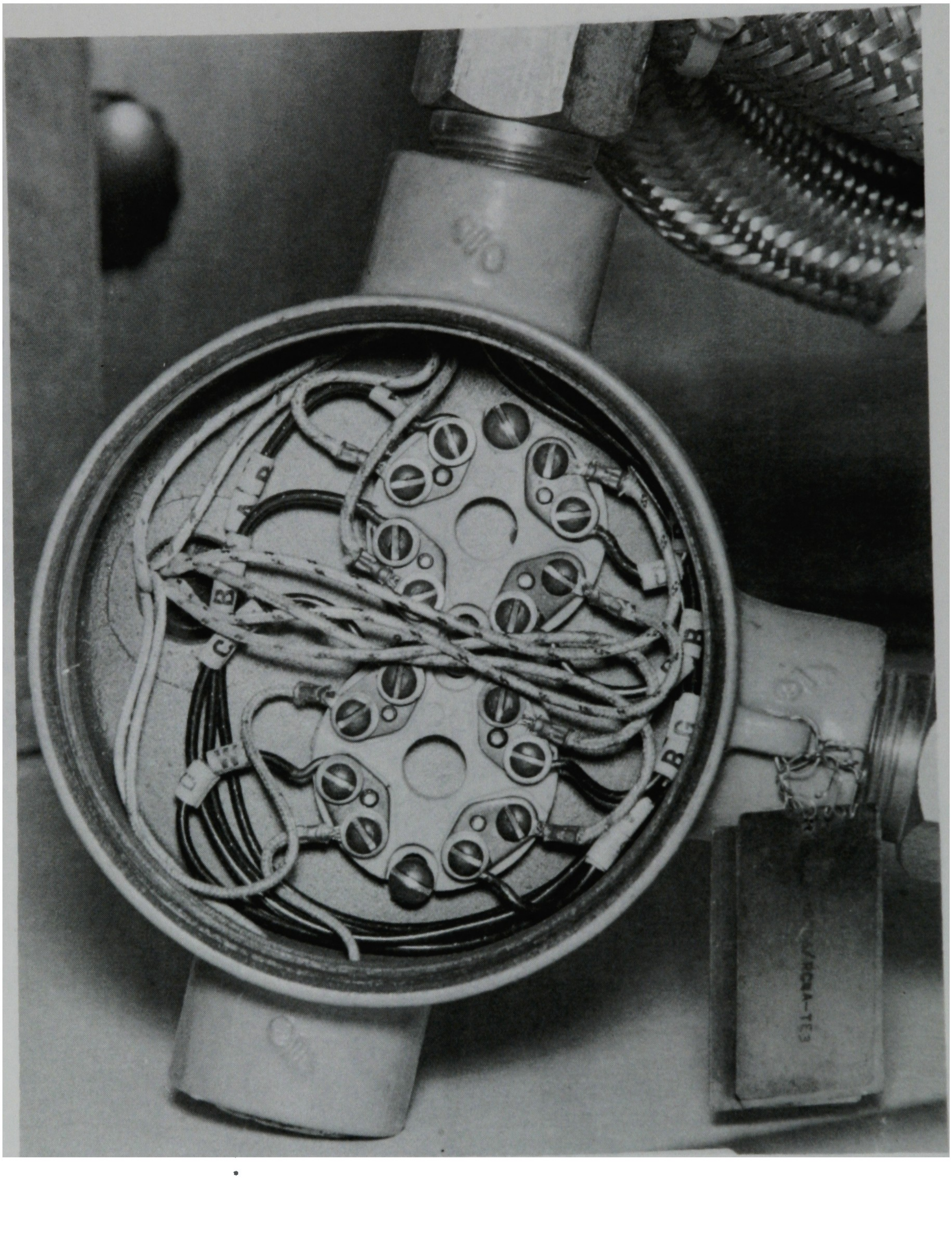
TESTED 11 JULY 1984

TARGET TEMP		REF RTD*	ELEMENT 1	ELEMENT 2
ICE POINT	RESISTANCE	199.995	100.323	100.092
	TEMP	.105	.348	.015
AMB	RESISTANCE	216.08	108.46	108.23
	TEMP	20.360	20.746	20.440
93°C (200°F)	RESISTANCE	272.25	136.53	136.34
	TEMP	92.094	92.159	91.990
204°C (400°F)	RESISTANCE	357.70	179.40	179.09
	TEMP	204.342	204.350	203.91
316°C (600°F)	RESISTANCE	439.04	220.10	219.77
	TEMP	314.96	314.65	314.60

*Rosemount model 162N20013
S/N 1471







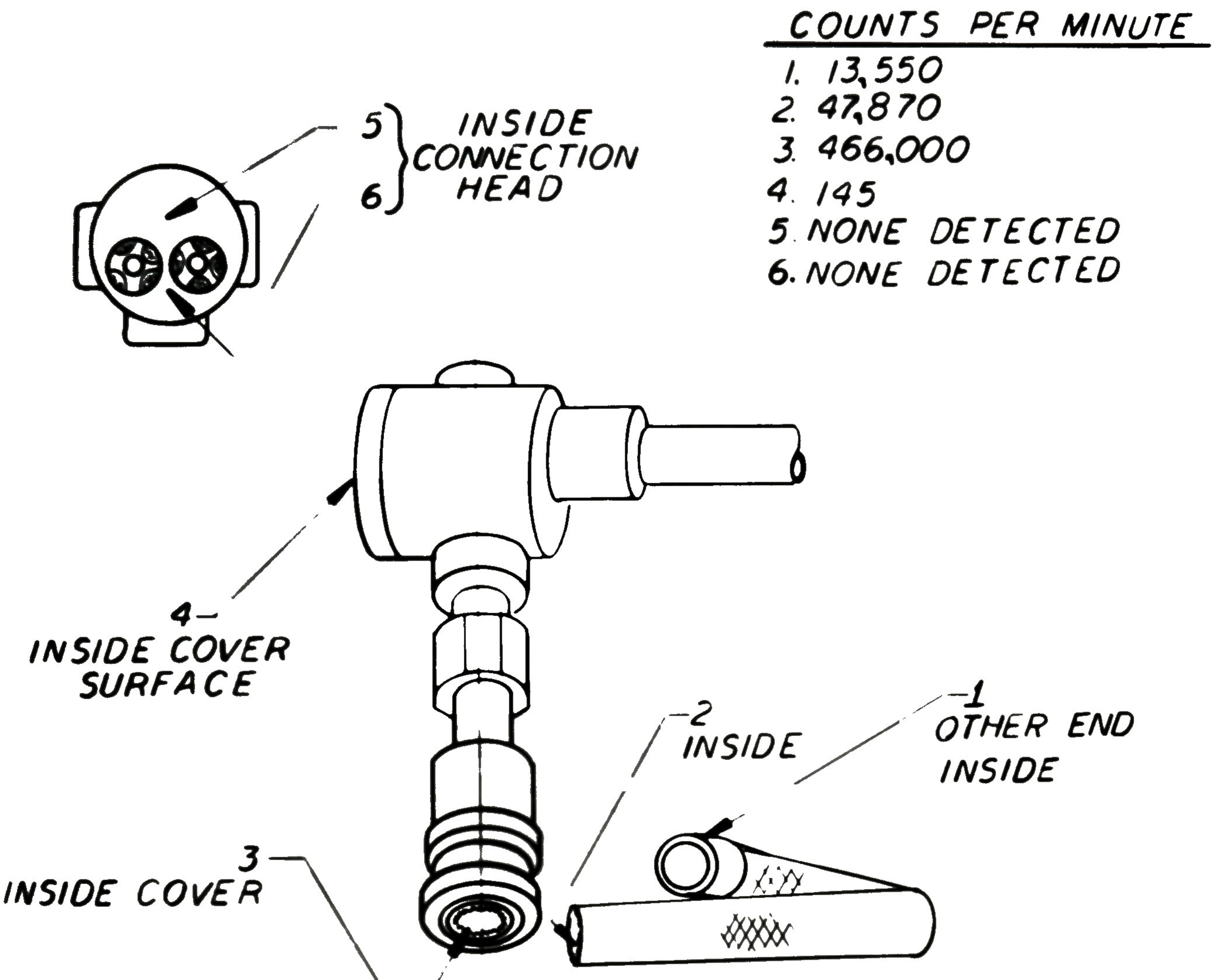
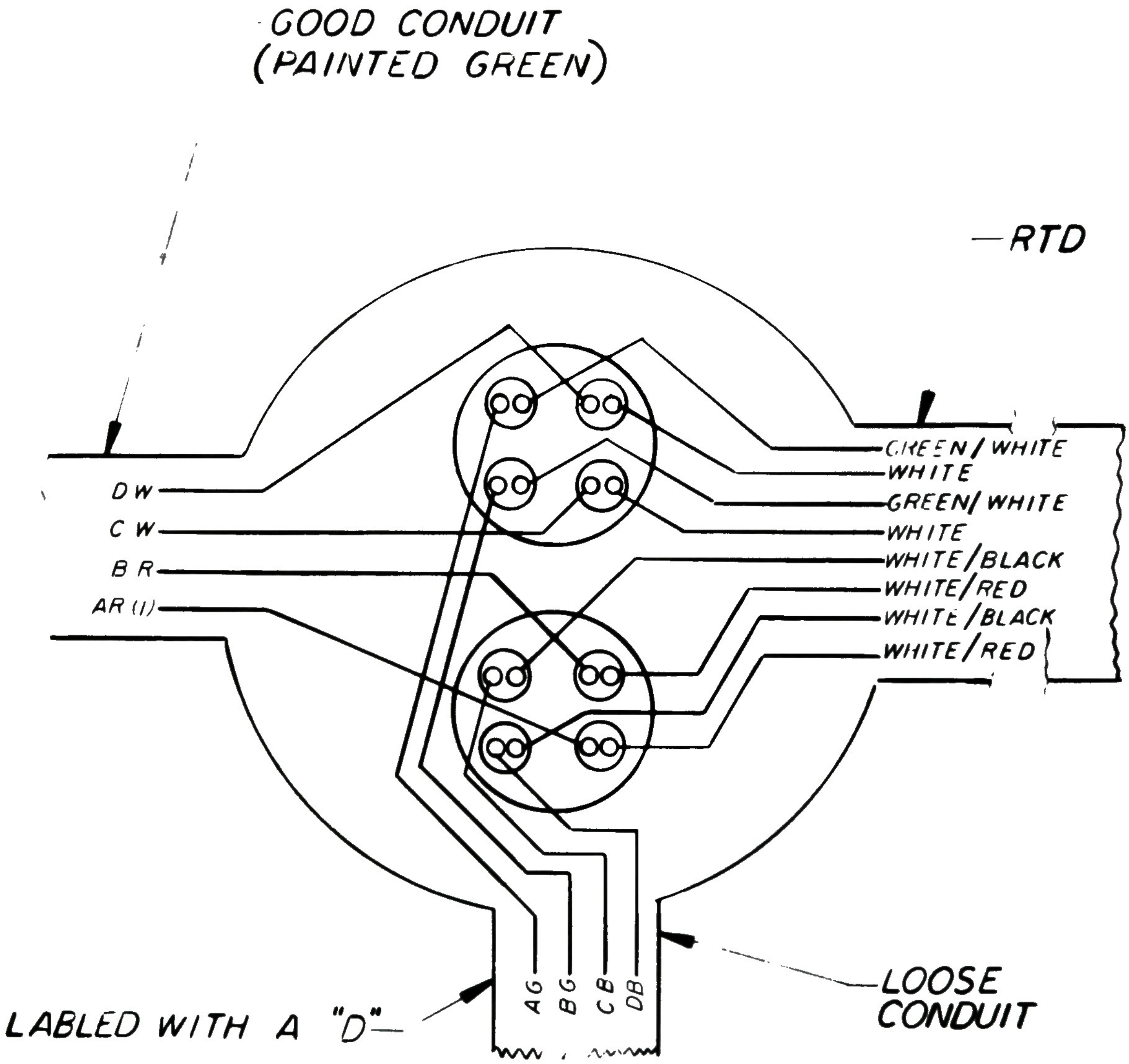
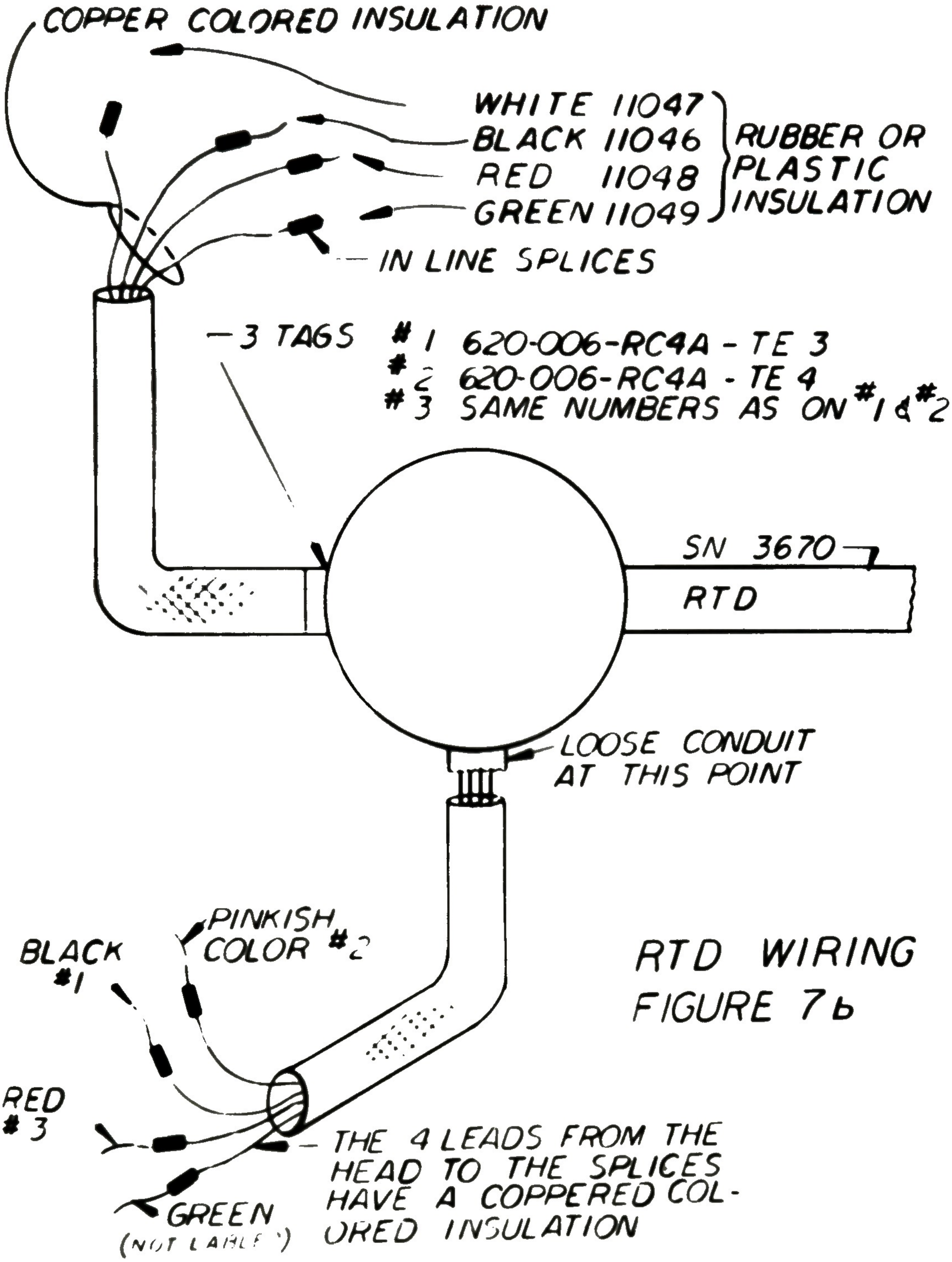


FIGURE 6 - CONTAMINATION LEVEL



RTD WIRING
FIGURE 7a



RTD WIRING
FIGURE 7b

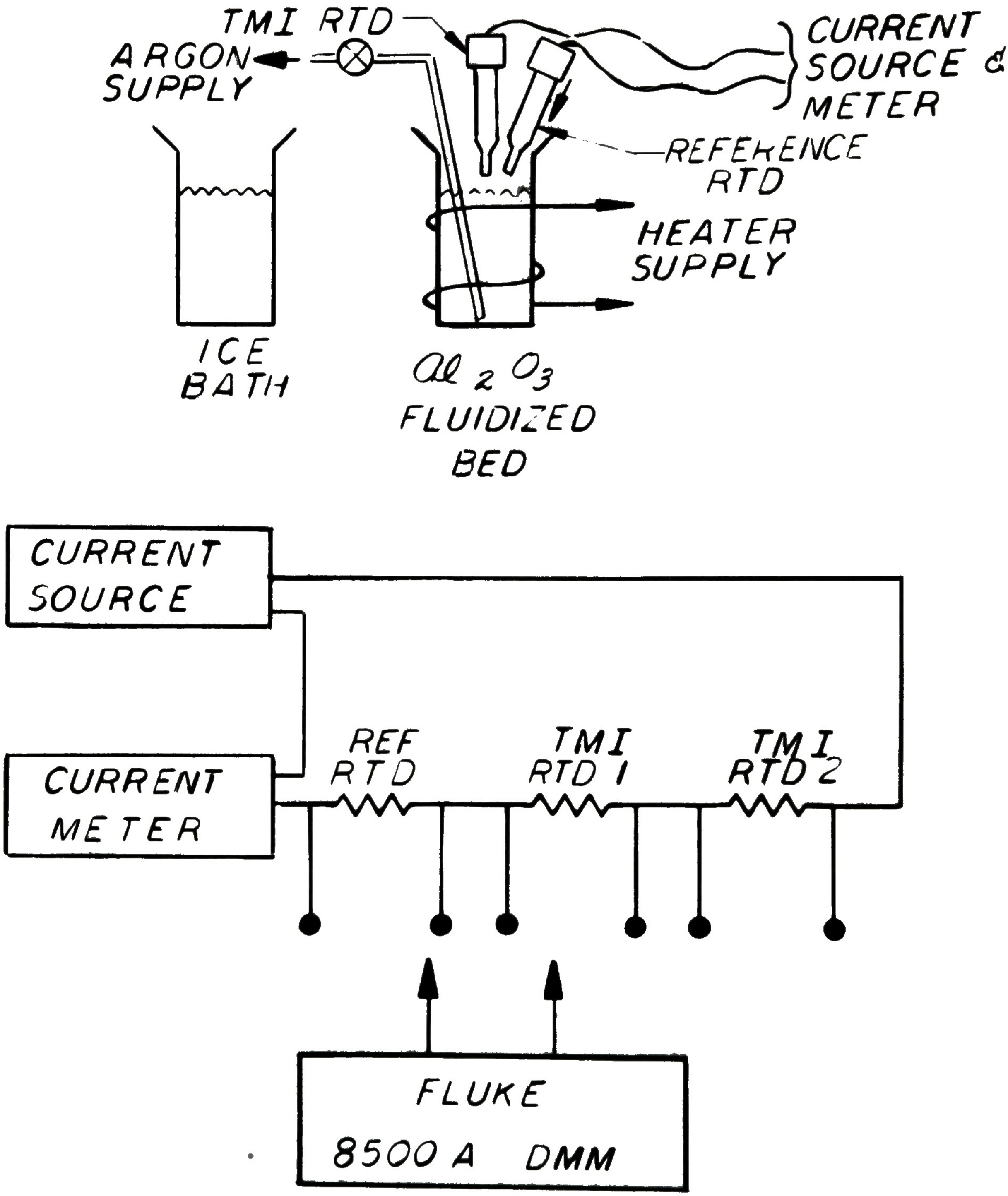


FIGURE 8 CALIBRATION CHECKS